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EFFICIENCY OF WORK AT VARYING INTENSITIES.

THE OHIO STATE UNIVERSITY, PH.D. 1979

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Efficiency of Work at Varying Intensities

Dissertation

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

Daniel J. Delio

*****

The Ohio State University

1979

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This work is dedicated to the three people who made it possible.

My mother: She instilled in me a love of knowledge at an early age.

My father: His physical labor allowed me the luxury of pursuing those things which were important to me.

Julie: She helped me to develop emotionally by unselfishly supplying friendship and love, even though at times I appeared ungrateful.
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PUBLICATIONS


FIELDS OF STUDY

Physical Education
Exercise Physiology. Professors Edward L. Fox and Robert L. Bartels
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Chapter I
Introduction

It can be said with reasonable certainty that current opinion is, that the most efficient way to perform a given amount of work is to employ an even pace. This concept can be found in books on coaching (5,7) and in certain research reports (16,26). Yet, there is available data that suggests equal efficiency of aerobic and anaerobic metabolism (11). Ignoring environmental resistance, such as that caused by air and water, and assuming equal efficiencies for aerobic and anaerobic metabolism, no clear reason for a greater economy of steady rate work is immediately discernable. Non-steady rate work should have an identical cost.

A second problem associated with non-steady rate work is monitoring the intensity at which it is performed. Investigators utilizing steady rate work have supplied evidence that heart rate during the first few seconds of recovery is indicative of heart rate during exercise (3,4,18). Therefore, by merely measuring heart rate immediately after exercise, the intensity of that exercise can be determined. This is not the situation when an exercise is performed in a non-steady rate condition. Under such circumstances, no
way of monitoring exercise intensity, other than observations made during exercise is employable.

**Purpose of the Study**

This study attempted to seek answers to two questions. The first answer sought concerned the current opinion on pacing. That the most economical way to work is by employing steady rate work has been accepted by many. This investigation attempted to reconfirm or discard this idea.

The second part of the study attempted to find a way to monitor the intensity of a non-steady rate work task by using recovery heart rate. It was thought that this could be of benefit to people involved in an organized program of physical conditioning.

**List of Terms and Abbreviations**

1. Energy cost. The amount of energy required to complete a given task. Also referred to as energy expenditure. This is directly related to oxygen cost.

2. $F_{ECO2}$. The fractional concentration of carbon-dioxide in expired air.

3. $F_{EO2}$. The fractional concentration of oxygen in expired air.

4. HR. Heart rate. Most often expressed in beats per minute.
5. Isokinetic. A form of muscular contraction where the velocity of motion of the limb involved is constant.

6. Kpm. Kilopondmeter. A unit of work which is equal to the amount of work accomplished when a one kilogram weight is moved one meter.

7. Oxygen cost. The amount of oxygen used in order to complete a task.

8. Oxygen debt. The amount of oxygen consumed during recovery from exercise which is in excess to that amount of oxygen normally consumed while at rest.

9. Oxygen deficit. The amount of oxygen not consumed during an exercise period which would have been required had the exercise been performed with energy derived exclusively from aerobic sources.

10. \( \dot{V}_{EATFS} \). Expiratory ventilation. The amount of air a person expires, expressed as a volume under ambient conditions of temperature, pressure, and fully saturated with water.

11. \( \dot{VO}_2 \). Volume of oxygen consumed. This measure refers to the amount of oxygen a person consumes over a given period of time. It is most often expressed in liters per minute (l/min) or milliliters per minute per kilogram of body weight (ml/kg.min).
12. $V_{ESTPD}$. Expiratory ventilation. The amount of air a person expires corrected to a volume at a standard temperature of $0^\circ C$, one atmosphere pressure, and dry.
Chapter II
Review of Literature

As is true for most issues, concerning the question as to how a given bit of exercise should be performed, there is a current opinion based on present knowledge. Modern coaching philosophy calls for even pacing to accomplish the most economical use of energy. One of the objects of this study was to determine the validity of this precept.

This literature review was undertaken to discover if research findings support this view. With this in mind, research dealing with the efficiency of work and the various energy systems was perused. As can be expected more than one model can be constructed that fits what we must assume to be the valid results of research performed to this date.

The question of oxygen cost is both complicated and interesting. Not only did it have to be decided if different conditions created changes in the oxygen cost of work, but what was an adequate way of measuring such changes also had to be decided. Many approaches have been used to answer these questions. Some investigators have used simple methods to gain practical solutions and others have used very
sophisticated means to arrive at conclusions of valid theoretical, but scant practical application.

Together with literature pertinent to the topic of work efficiency and cost, reports concerning HR response to exercise were surveyed. The present investigation also sought to find if any relatively simple method to quantify non-steady rate exercise, by using recovery HR, existed.

**Literature Related to Oxygen Cost**

**Asmussen, 1970 (1).** By occluding blood flow to a working leg, this researcher attempted to find changes in the total oxygen consumption for a given task. Total oxygen consumption for a cycling task was first determined. Then the task was repeated with blood flow restricted to a leg. The investigator found that if blood flow was restricted, the total oxygen consumption became greater.

In a second condition, blood flow during rest was impeded by means of a blood pressure cuff. If blood flow was interfered with for longer than five minutes a larger than expected oxygen debt was created.

Unfortunately, no mention was made of HR or breathing rate changes which could have accounted for these increases.

**Mathews, Bowers, Fox, and Wilgus, 1963 (17).** In this study subjects pedaled a bicycle ergometer for six minutes
and accomplished 53,064 ft/lbs of work. This was done by riding at 200 watts for six minutes, or 100 watts for two minutes, 200 watts for two minutes, and 300 watts for two minutes, or the reverse. Net oxygen cost for the entire exercise was calculated. The results were that the steady rate condition yielded the lowest oxygen cost. The conditions of increasing and decreasing work loads did not differ from each other, but required more oxygen than the steady work condition.

Whipp and Wasserman, 1969 (25). The purpose of this study was to calculate the efficiency of work. Certain assumptions were made in order to do this. The ratio of ATP production to oxygen consumption was assumed to be 3. The amount of energy released when one mole of ATP is hydrolized to ADP, under physiological conditions, was assumed to be 11,000 calories. The caloric equivalent of 340 kpm/min was considered to be 780 cal/min. Using these figures and after experimentally determining the net cost to the subjects was 545 ml oxygen/min at a work load of 340 kpm/min, it was concluded that the efficiency of work was 49%.

Hagberg, Giese, and Mullin, 1975 (13). A constant source of disagreement between cyclists is at what speed a bicycle should be pedaled. This study sought to answer this question. Trained cyclists rode at a constant work load, but
varied crank speed. The optimal crank speed was shown to be 90-100 rpm for this group. A deviation from this speed of greater than 20 rpm caused $\dot{V}_E$ to rise 15-25% and $\dot{V}O_2$ to increase by 10-15%.

**Gaesser and Brooks, 1975 (10).** This paper questioned the validity of many previous papers. It showed that perhaps net oxygen cost was a poor indicator of efficiency. The main importance of this paper was in its defining of the four different types of efficiency calculations. They were described as follows:

- **gross efficiency** = work accomplished/energy expended
- **net efficiency** = work accomplished/energy expended above rest
- **work efficiency** = work accomplished/energy expended above a no load condition
- **delta efficiency** = delta work/delta energy expended

Considering that the relationship between energy expended and work intensity is linear or slightly exponential, efficiency should remain constant or decrease slightly as work rate increases. Only delta efficiency calculations reveal such results consistently. Although, when the relationship is perfectly linear, as in cycling, then work efficiency reveals similar results.
Donovan and Brooks, 1975 (8). The authors state in this article that if cycling is the means of work employed, then work efficiency can be used for the calculation of efficiency.

Gladden and Welch, 1978 (12). In order to compare the efficiency of aerobic and anaerobic work, the investigators changed the fractional concentration of oxygen in the inspired air (F\textsubscript{1}O\textsubscript{2}). They assumed that as F\textsubscript{1}O\textsubscript{2} became lower, more energy would have to be derived from anaerobic sources. In addition to being exposed to lowered F\textsubscript{1}O\textsubscript{2}, the subjects work at 20, 50, and 70% of maximum aerobic ability. As F\textsubscript{1}O\textsubscript{2} was lowered, the concentration of lactic acid in the blood increased linearly. This was taken to mean that the efficiency of deriving ATP from aerobic and anaerobic sources is the same.

Literature Related to Heart Rate

Bowen, 1904 (3). In this study the time course of HR during and after exercise was reported. Subjects rode a bicycle ergometer at 400 kpm/min. The investigator observed a quick initial rise in HR, followed by a slower secondary rise. At cessation of work a very sudden drop in HR was noted.

Shephard, 1966 (23). The main concern of this study was to see if HR during recovery from exercise could be used to indicate the physical fitness of a person. The subjects
exercised at various submaximal intensities and also at maximum ability. The results of this study showed that following submaximal work, HR is related to the fitness of a person. The better conditioned person will have a lower HR during work and during the first few moments of recovery, than his unconditioned counterpart.

Following maximum exercise, HR did not correlate well with a person's degree of conditioning. The authors felt that this was due to all subjects having similar HR during maximum exercise. There was, however, a difference in the rate at which recovery HR returned to resting levels between conditioned and non-conditioned groups. As expected, conditioned subjects returned to resting values more quickly.

McArdle, Zwiren, and Magel, 1969 (18). This study was designed to ascertain the validity of post exercise HR as an indicator of HR during exercise. The subjects performed exercise bouts of various intensities. HR was recorded during work and immediately after. It was found that HR during the first 10 seconds of recovery was only 3% lower than HR during exercise.

Shapiro, Shoenfeld, and Shapiro, 1976 (22). Eighty-four subjects were used to determine the relationship between HR during work and HR during the first 5-15 seconds of recovery.
While HR during recovery was 11.5% lower than during exercise, the correlation between the two was $r = -0.98$. The equation relating the two variables was:

$$RHR = 0.176 \text{ WHR} - 0.009 \text{ DHR} - 0.006 \text{ VO}_2 \text{ max} - 3.003$$

where $RHR$ is the heart beat in the first 5-15 seconds of the recovery period, WHR is the HR at work, and DHR is the difference between HR at work and at rest. $\text{ VO}_2 \text{ max}$ is expressed in ml/kg·min.

Nandi and Spodick, 1977 (19). This investigation found HR to be dependent on work load. Three work loads, consisting of 50, 100, or 150 W were used. HR during work of 150 W was 158 beats/min. Also, recovery to resting was longer after work at 100 and 150 W than after work at 50 W. The relationship between HR during recovery and HR during work was not determined.

Literature Related to $\text{ VO}_2$ During Cycling

Hermansen and Saltin, 1969 (16). In a study involving 55 subjects of various levels of fitness, $\text{ VO}_2 \text{ max}$ was determined while the subjects rode a bicycle ergometer. The reported mean value for $\text{ VO}_2 \text{ max}$ was 3.90 l/min.

Faulkner, Roberts, Elk, and Conway, 1971 (9). The reported value for $\text{ VO}_2 \text{ max}$ while pedaling a bicycle ergometer
in this study was determined by observing eight subjects. This value was 3.43 l of oxygen/min.

**Literature Related to Steady State**

**Gilbert, Auchicloss, and Baule, 1967 (11).** In an attempt to determine how much time the body requires to adjust to work, these investigators asked subjects to perform two exercise bouts. One condition required riding a bicycle on a treadmill at 2.7 km/hr (1.7 mph) on a 3% grade. The other condition required riding at 4.8 km/hr (3 mph) on a 3% grade. Oxygen uptake during this work was 1,205 ml/min and 1,852 ml/min respectively. It was found that at these work loads that 1.5-3.0 minutes were required to reach steady state.

**Whipp and Wasserman, 1972 (26).** This study was designed to determine if the attaining of steady state VO$_2$ is related to the intensity of the exercise performed. It was found that as intensity of exercise increases, the body will take longer to reach steady state. It is interesting to note that with subjects who were better conditioned, steady state was reached sooner than in unfit subjects.

**Bason, Billings, Fox, and Gerke, 1973 (2).** Subjects performed exercise on a bicycle ergometer at 30, 60, and 80% of VO$_2$ max. Altitudes of 223, 2,286, and 3,810 meters were simulated in a hypobaric chamber. The investigators attempted
to find if any relationship existed among intensity of work, altitude, and attaining a \( \text{VO}_2 \) steady state. Time to reach steady state was shown to be independent of altitude. At work loads of 30 and 60% of maximum aerobic capacity, steady state was reached in 6 and 20 minutes, respectively. When working at 80% of maximum aerobic ability steady state was not reached.

Hagberg, Nagel, and Carlson, 1978 (14). This study was designed to determine if the achieving of steady state is related to work load. The authors concluded that as work load increases, it takes longer to reach steady state.

Hagberg, Mullin, and Nagel, 1978 (15). Oxygen consumption was observed to rise constantly in subjects working on a bicycle ergometer for 20 minutes. At 65 and 80% of \( \text{VO}_2 \) max, the rise in oxygen consumption was 8 and 10% of the value at five minutes respectively. Portions of the increase were attributed to an increase in body temperature and an increased cost of ventilation.

**Literature Related to Equipment**

Daniels, 1971 (6). In this report the author describes a breathing valve which has very desirable characteristics for use during tests requiring a high \( V_E \). The dead space is small, being only 70 ml. Resistance to flow is also slight, being 0.5 cm of water at a high flow rate of 300 ml of air/min.
Wilmore and Costill, 1974 (27). The authors described a semiautomated system for the determination of $\dot{V}O_2$. It consists of a digital volume display, a valve which would permit the drawing of a sample of gas from a mixing chamber, and two rapid response oxygen and carbon dioxide gas analyzers. The ease of operation and the relatively low cost of assembly made this system very attractive.

Summary

The studies reviewed appear to indicate that the question of work efficiency is far from answered. Each technique, as described by Gaesser and Brooks (10), offers a different view. The delta efficiency technique offers a theoretical answer which may not be of any meaning to a person taking part in an athletic competition. Yet, information about total oxygen cost, may give this person valuable information.

The information presented in studies concerning work efficiency also depicts how the study must be done. Being concerned with sudden short bursts of effort during a race, oxygen consumption over a period of time involving both the work period and recovery must be measured, since previous data show that steady state levels will not always be reached under the conditions employed during the present study.
Since HR during recovery has only been studied after steady rate work, what to expect with respect to this variable is unclear.
Chapter III
Methods and Procedures

Taking into account the apparent lack of agreement concerning work efficiency, a study was designed with the purpose of casting more light on this subject. A design which would yield practical information was sought. It was thought that the greatest amount of useful information could be gained by using a design which measured the gross expenditure of energy during activity. The following is a description of this design.

Subjects

The subjects were seven normal men who volunteered to take part in the study. All were physically active and were familiar with the equipment and the specific tests used. A description of the subjects is shown in Table 1.
Table 1
Subject's Vital Data

<table>
<thead>
<tr>
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<th>X</th>
<th>± SD</th>
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<tbody>
<tr>
<td>Age, years</td>
<td>25.14</td>
<td>2.19</td>
</tr>
<tr>
<td>Weight, kilograms</td>
<td>76.4</td>
<td>5.69</td>
</tr>
<tr>
<td>Height, centimeters</td>
<td>182.8</td>
<td>10.06</td>
</tr>
<tr>
<td>VO₂ max, l/min</td>
<td>3.97</td>
<td>0.64</td>
</tr>
<tr>
<td>HR max, beats/min</td>
<td>182.57</td>
<td>11.04</td>
</tr>
</tbody>
</table>

Design

Each subject performed an exhaustive bout of exercise on an isokinetic bicycle ergometer. At this time VO₂ max and HR were measured. The task involved riding the ergometer at a constant pedaling rate and at a work load which increased every two minutes. This continued until the subject could no longer maintain the work output. VO₂ was measured the second minute of each level. When HR reached 175 beats/min, VO₂ was measured every minute.

All subjects then engaged in five different work conditions. The order the conditions were experienced was randomly assigned to each subject. Subjects were tested no more than twice a week. All conditions lasted four minutes and for each condition the total amount of work performed was equal. The amount of work performed was not identical for
each subject. Condition I consisted of riding at a constant work load. The remaining four conditions involved working for three minutes at a relatively low intensity (L) and for two 30 second intervals at a relatively high intensity (H). The low intensity work corresponded to 70% of each subject's maximum aerobic ability. The high intensity work was above the aerobic ability of the subject. In summary, the five conditions were structured as follows:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
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<tr>
<td>I</td>
<td>steady rate (SR)</td>
</tr>
<tr>
<td>II</td>
<td>1 minute H, 3 minutes L (H,L)</td>
</tr>
<tr>
<td>III</td>
<td>3 minutes L, 1 minute H (L,H)</td>
</tr>
<tr>
<td>IV</td>
<td>30 seconds H, 3 minutes L, 30 seconds H (H,L,H)</td>
</tr>
<tr>
<td>V</td>
<td>1 minute L, 30 seconds H, 1 minute L, 30 seconds H, 1 minute L (L,H,L,H,L)</td>
</tr>
</tbody>
</table>

Before exercise the subjects remained seated on the ergometer for five minutes. After the exercise the subjects immediately left the machine and took a position in a chair, where they remained for 15 minutes.

Oxygen consumption was measured every minute during rest and recovery and every 30 seconds during exercise. HR was measured every minute during rest, and every 30 seconds during exercise. During recovery HR was measured for the
first 10 seconds, from 30-40 sec, 60-70 sec, 90-100 sec, 120-130 sec, 150-160 sec, 180-190 sec, 210-220 sec, 240-250 sec, 270-280 sec, 300-310 sec, and every minute thereafter.

Three ml of blood were drawn from the anticubital vein for determination of lactic acid. This was done before exercise and two minutes after the cessation of work. Difficulties with this method of lactic acid analysis made necessary the change to a micro technique. This method required only 25 microliters of blood obtained by puncturing a finger with a sterile lancet.

Equipment

The system which was used to calculate VO$_2$ was semi-automated. The volume of gas inspired was measured and displayed on a digital readout. Expired air from the subject was channeled to a mixing chamber and from here samples were drawn into anesthesia bags. By rotating a valve, samples of gas from the anesthesia bags could be drawn thru gas analysers and $F_{E}O_2$ and $F_{E}CO_2$ could be determined. The system incorporated three bags. While one was being filled, one was being analyzed, and the third was being evacuated and readied for the introduction of a sample. This system is described in great detail by Wilmore and Costill (27).
This system, which was used to measure VO₂, contained the following equipment:

CD 4. A gas meter manufactured by Parkinson Cowan Inc.
Daniels valve. A breathing valve manufactured by Phemco Inc.
Mixing chamber. A cylindrical chamber which allows for the mixing of expired gases.
Wilmore valve. A three way valve on which three anes­thesia bags are attached. The function of this valve was explained above.
OM - 11. A rapid response oxygen analyzer produced by Beckman Inc.
LB - 2. A rapid response carbon dioxide analyzer manufactured by Beckman Inc.

In order to measure HR the following equipment was used:

1500 B. An electrocardiograph machine manufactured by Hewlett Packard Co.

The following piece of equipment served as the exercise machine:

Fitron. This is a unique piece of equipment. It is the only available bicycle ergometer employing an isokinetic sys­tem. It is produced by Lumex Inc.
Total Oxygen Cost

To partition metabolism into separate categories of rest and exercise is of little value. During a time of activity the entire oxygen consumption is indicative of the energy expenditure of the organism. Therefore, total oxygen consumption, or cost, was considered in the present study.

In order to determine total oxygen cost of the cycling task, $\dot{V}O_2$ was measured during exercise and during 15 minutes of recovery. The $\dot{V}O_2$ for this entire period of time was considered to represent the total oxygen cost of the activity.

Oxygen Deficit

The oxygen deficit incurred during work was calculated, to determine if the energy contributions of aerobic and anaerobic metabolism were similar under all five conditions. Since the subjects were at times working at levels above maximum aerobic ability, the energy expenditure at these levels could not be measured by determination of oxygen uptake. Therefore, regression lines representing $\dot{V}O_2$ vs. work load were generated for each subject. Corresponding values for oxygen consumption were determined using these lines (See Appendix H). At points above maximum aerobic ability the line was extrapolated to achieve values at these levels. Since in cycling the relationship represented by these lines
is linear, this method can easily be justified. The differences between these calculated VO₂'s and those measured during work were the total deficits.

**Determination of Heart Rate**

HR was monitored using a bipolar lead system. The paper speed of the electrocardiograph was set at 25 mm/sec. In order to determine HR at any given moment six consecutive R waves were marked. The distance between the first and sixth wave was measured. HR was then determined using the following equation:

\[
HR = \frac{7500 \text{ mm/min}}{D}
\]

where

\[D = \text{the distance between the first and sixth R wave expressed in mm.}\]

**Limitations**

During the course of the study certain concessions were made which were beyond the control of the investigator. They are mentioned here so as to serve the purpose of improving future studies in this area.

1. Blood lactic acid. An attempt was made to measure this parameter. Due to reasons of an unknown nature, values concerning these data were not reliable.
2. Time of testing. This was not controled. Subjects were tested when they were available. No subject participated in strenuous activity or had eaten immediately prior to being tested.

3. Perception of work load. Due to the need to change work rate quickly, the specific task was explained to the subject immediately before testing started. Heart rate response to the work load may have been influenced by some preconceived notion on the part of the subject, but changes in metabolic responses due to a mental factor is highly doubtful.
Chapter IV
Results

The study attempted to find the most economical way to accomplish a given task on a bicycle ergometer. Gross oxygen cost, oxygen deficit, and oxygen kinetics during exercise were studied. Heart rate during and following exercise was monitored with the hope of finding a relatively simple way to gauge the intensity of non-steady state exercise.

Total Work

Table 7 (Appendix A) shows the total amount of work in thousands of kpm, performed by each subject. Results of an ANOVA performed on these data show that at the .05 level of significance there was no difference in the total amount of work between conditions. The results of the ANOVA appear in Table 2.
Table 2
Analysis of Variance for Total Work

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>SS</th>
<th>d.f.</th>
<th>MS</th>
<th>F</th>
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</thead>
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<td>2.70</td>
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<td>Between Subjects</td>
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<tr>
<td>Error</td>
<td>0.645</td>
<td>24</td>
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<tr>
<td>Total</td>
<td>26.052</td>
<td>34</td>
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</table>

Total Oxygen Cost

Table 9 (Appendix G) shows the total oxygen cost for each trial in liters/min. This represents the gross oxygen consumption during four minutes of exercise and 15 minutes of recovery. Table 3 shows the results of an ANOVA performed on these data. At the .05 level of significance there was no difference between the five conditions.

Table 3
Analysis of Variance for Total Oxygen Cost

<table>
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<td>Total</td>
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Steady State

Figure 1 shows the pattern of oxygen consumption during work for each condition. A visual inspection of this graph gives the impression that steady state is reached quicker in condition II (H,L) than in any other case. An ANOVA was performed using the data represented by this graph. Tukey's test of Honestly Significant Difference was used for the multiple comparisons of means. During the early stages of work, while $\text{VO}_2$ is rising, consecutive measures of this parameter should be different. When two consecutive values are not statistically different, steady state has, for the purpose of this study, been reached. The .05 level of significance has been used to determine differences.

The results of the test are shown in Table 4. In condition I (SR), IV (H,L,H), and V (L,H,L,H,L) steady state was reached in 90 seconds. In conditions II (H,L), and III (L,H) steady state was reached in 60 seconds. In condition III (L,H) with one minute of high intensity work at the end of exercise, there was demonstrated a second rise in $\text{VO}_2$ at that time. In addition to this, the original steady state level achieved in condition III (L,H) was significantly lower than that reached in condition II (H,L). The higher level was eventually reached by condition III (L,H) during
the last minute of exercise. These results appear to indicate that one minute of high intensity exercise at the beginning of exercise increases the speed at which steady state is attained.

Table 4

Analysis of Variance for Oxygen Consumption

<table>
<thead>
<tr>
<th>Source of Variation</th>
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<th>MS</th>
<th>F</th>
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</thead>
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<td>A x C</td>
<td>3780.78</td>
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<tr>
<td>B (time)</td>
<td>25334.14</td>
<td>7</td>
<td>3619.16</td>
<td>133.421*</td>
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<td>B x C</td>
<td>1139.29</td>
<td>42</td>
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</tr>
<tr>
<td>A x B (interaction)</td>
<td>5044.38</td>
<td>28</td>
<td>180.15</td>
<td>16.406*</td>
</tr>
<tr>
<td>A x B x C</td>
<td>1844.82</td>
<td>168</td>
<td>10.98</td>
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</tr>
<tr>
<td>C (subjects)</td>
<td>30459.69</td>
<td>6</td>
<td>5076.61</td>
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</tbody>
</table>

* indicates significance at the .05 level

Oxygen Deficit

The data representing the oxygen deficits accumulated during the five different exercise conditions appears in Table 8 (Appendix B). An ANOVA was performed using these data. A Fisher Least Significant Differences test was used to show where significant differences existed. The results of this analysis are shown in Table 5.
Table 5

Analysis of Variance for Total Oxygen Deficits

<table>
<thead>
<tr>
<th>Source of Variation</th>
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<th>d.f.</th>
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<td>0.446</td>
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<td>Between Subjects</td>
<td>5.262</td>
<td>6</td>
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</tr>
<tr>
<td>Error</td>
<td>1.707</td>
<td>24</td>
<td>0.711</td>
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<tr>
<td>Total</td>
<td>8.754</td>
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<td></td>
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</table>

* indicates significance at the .05 level

The total deficit acquired during condition IV (H,L,H) was smaller than that acquired during condition III (L,H). The deficit produced during condition V (L,H,L,H,L) was lower than that of conditions III (L,H) and IV (H,L,H). The smallest deficit was seen in condition II (H,L) and this was significantly lower than all other deficits, except for that of condition V (L,H,L,H,L).

Combining these results with those previously mentioned, it appears that one minute of high intensity work during the beginning of exercise causes steady state to be reached sooner than in the case where a steady rate exercise is employed. This more rapid rise to steady state then precipitates the accumulation of a smaller oxygen deficit even though identical amounts of work are performed.
Heart Rate

Figure 7 (Appendix E) shows HR during rest, exercise, and recovery during conditions I thru IV. This graph indicates a rapid rise in HR at the onset of exercise. With the cessation of work there is an initial rapid fall in HR, followed by a more gradual drop. This has been shown to be true in many previous studies involving HR (3, 4, 18).

HR during the first 15 seconds of recovery appears to be closely associated with HR during the last moments of exercise with a correlation of $r = 0.97$. Recovery HR during this time was only about 1.6% lower than exercise HR. HR during the later stages of recovery in conditions III (L, H) and IV (H, L, H), where there was a period of high intensity work at the end of exercise, seems to be related to HR during the steady state portion of exercise, but was more closely related to HR during the first few moments of recovery. In condition III (L, H) HR after 30 seconds of recovery has a correlation of $r = 0.52$ with HR during the steady state portion of exercise. When HR after 30 seconds of recovery is correlated to HR during the first 15 seconds of recovery, an $r = 0.74$ is obtained. Similarly, in condition IV (H, L, H) when analogous comparisons are made, HR after 30 seconds of recovery has a correlation of $r = 0.94$ with HR during the steady state portion of exercise and an $r = 0.96$ with HR during the first 15 seconds of recovery.
It seems that HR during recovery is most closely related to HR at the very beginning of recovery. This seems to be a relationship not affected by a bout of high intensity work at the end of exercise.

HR in all cases, except condition V (L,H,L,H,L), reached steady state values, as defined for VO₂ in this study, within 60 seconds. In condition V (L,H,L,H,L) HR reached this level in 90 seconds. These results appear in Table 6. Even though HR did not show increases from one collection period to the next, in all cases except condition II (H,L) HR at the end of exercise was significantly higher than HR after one minute of exercise. In condition II (H,L) HR at the end of exercise was significantly lower than in all other cases.

Table 6
Analysis of Variance for Heart Rate

<table>
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<tr>
<th>Source of Variation</th>
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<tr>
<td>A x C</td>
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<td>.0089</td>
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<tr>
<td>B (time)</td>
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<td>.0378</td>
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<td>B x C</td>
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<td>.0320</td>
<td></td>
</tr>
<tr>
<td>A x B (interaction)</td>
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<td>.0676</td>
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<td>A x B x C</td>
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<tr>
<td>C (subjects)</td>
<td>13.222</td>
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<td>2.204</td>
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</tbody>
</table>

* indicates significance at the .05 level
The first reported result may appear trivial, but it is important. The total work performed was identical in all conditions. In this study a unique form of bicycle ergometer was used. It is always difficult to accurately gauge work on a bicycle ergometer. The need to instantly change work output would appear to complicate the matter even more.

The Fitron was perfectly suited to the task. In effect it can respond as quickly as the subject. This is a unique feature. On a conventional ergometer time is required to adjust belt tension and on a treadmill the motor needs considerable time to increase speed. These features would make it difficult to perform equal amounts of work under a steady rate condition and a condition of varying intensities. The lag time in adjusting the work output would be present in the second case, but not the first.

This problem was circumvented by use of the Fitron. This piece of equipment allows for a better study of work, involving quick changes in intensity, than was previously within our capability. Not only does it allow for instantaneous changes in work rate, but it gives a digital readout of work performed.
Having established the reliability of the equipment used, conclusions about the cost of work on this equipment can be made. The results of this study show that a given amount of work on a bicycle ergometer will cost a constant amount of energy. This situation is true regardless of how the work is performed, i.e. aerobically, or anaerobically. This statement does not agree with data published by Mathews et al. (16).

This simple statement implies that both aerobic and anaerobic metabolism are of equal efficiency. This is in agreement with the conclusion of Gladden and Welch (12).

Oxygen consumption and gross efficiency have been disregarded by many because in some instances gross efficiency calculations give poor results. This has been discussed at great length by Gaesser and Brooks (10) and again by Donovan and Brooks (8). What the most practical calculation is has been ignored. Delta efficiency means very little to a performer.

As an example, a hypothetical situation will be presented. Two runners are moving at speed X. Runner A is consuming 2.0 l O2/min and runner B is consuming 2.5 l O2/min. If they were to increase their speed to 2X, we can safely assume an increase in VO2 would occur. It would not be unreasonable to assume runner A would now consume 3.0 l O2/min and runner B would consume 3.5 l O2/min.
A delta efficiency calculation would show both runners to be of equal efficiency. Both increased work load by the same amount and both increased energy expenditure by the same amount. The fact that one is expending 2.5 Kcals/min additional energy is not considered.

To emphasize even more strongly why gross oxygen consumption is important in this case, the following stipulation will be imposed on the performers. What if each had an identical \( \dot{V}O_2 \) max of 3.0 l/min. Surely, runner B would suffer from his additional energy expenditure. Simply stated, he could not run at this level.

For the same reason net efficiency is lacking. It also is not practical. From day to day resting \( \dot{V}O_2 \) will change as measured in the laboratory. Considering that energy expenditure at a given work load is fairly constant for a person, due to this change in resting \( \dot{V}O_2 \), net efficiency will change from day to day. Therefore, does this change in calculated net efficiency reflect an actual change in efficiency? Net cost will differ only as an artifact of measurement. No difference in working condition exists, it is the shifting of the baseline, rest, which is being observed.

The mistake is in referring to rest as zero work. The baseline for oxygen consumption is not rest. Rest is a
metabolically active state. Variation in resting VO₂ merely reflects the degree to which a person is attaining rest. The baseline for oxygen consumption is zero.

Perhaps the most interesting aspect of this investigation was the data associated with the attaining of physiological steady state. Articles cited in the review of literature have already investigated this phenomenon (2,14,15,26).

These studies have investigated the impact of work intensity or physical fitness on the attaining of steady state. In each case work was done in a steady rate condition. The results seem to indicate that physically fit individuals reach steady state sooner than their unfit counterparts (26) and that during high intensity work, steady state is achieved more slowly (11).

What was added to this previous work by the present study was conditions of varying intensity. The results seem to indicate that by beginning exercise with one minute of high intensity work and then reducing the intensity to a lower level, physiological steady state is more quickly reached. This is shown by the fact that condition II (H,L), which corresponded to the description above, not only reached steady state in terms of VO₂ sooner than the steady rate condition I (SR), but also accumulated a smaller oxygen deficit. This means that in condition II (H,L) more oxygen was supplied to
the working muscles, during exercise, than in condition I (SR). Therefore, aerobic metabolism was able to account for a greater percentage of the energy supplied during work in this condition. This is in spite of the fact that in condition II (H,L) the subject worked for one minute at a level that exceeded his VO2 max. While in condition I (SR) the entire effort was accomplished at an intensity below the aerobic ability of the subject.

Condition II (H,L) showed a different HR response as well. All conditions except V (L,H,L,H,L) reached steady state HR after one minute of exercise. In condition V (L,H,L,H,L) this level was reached 30 seconds later. Yet, while HR was not increasing significantly from one collection to the next, at the end of exercise HR was higher than after one minute of exercise in all cases except condition II (H,L). This suggests that the overall stress of condition II (H,L) was in some way less than that of other conditions.

These results are in contrast with many currently accepted ideas. Mathews et al. showed that steady rate work had a lower net cost than work of increasing or decreasing intensity (16). Current coaching philosophy is that a race should be performed at a steady pace for greatest economy. If this is not possible, Doherty suggests an ever increasing pace (7). In the present study an ever increasing pace caused
the greatest oxygen deficit to accumulate. An even pacing is advised by Counsilman (5). In the present study even pacing was not the work condition which yielded the smallest O

2 deficit or attained VO

2 steady state soonest.

If the findings of this study are true in cases using other forms of work, such as swimming and running, then performance in a race involving these activities may be improved by using an uneven pace. It follows that if a strong start followed by an easing of effort to approximately 70% of maximum ability speeds the onset of steady state and decreases the oxygen deficit, then this would be a reasonable thing to do. In theory, if two runners with identical ability are competing and one accumulates a smaller oxygen deficit, he should have an advantage, since he has gained more energy from aerobic sources and has kept his anaerobic sources reserved.

In addition to oxygen cost of exercise, HR response to exercise was also investigated. This study supports the results of several past studies (2,18,22). HR during the first ten seconds of recovery is a good indication of HR during the last moments of exercise. Condition III (L,H) and IV (H,L,H) gave us the opportunity to observe HR during recovery from exercise which contained an anaerobic burst of work during the last minute of performance. While a
relationship exists between HR during the later part of recovery and the steady state portion of exercise, in reality HR during recovery seems more closely related to HR during the last minute of exercise.

Unfortunately, this study did not reveal any easy way to monitor the intensity of a non-steady state exercise by using recovery HR. While relationships may exist, they are not of a nature which would allow prediction of exercise HR from recovery HR. It seems possible that a certain combination of low intensity and high intensity work may produce a HR at one minute into recovery which is predictable. Yet many combinations of work may produce this same HR at this same time. Therefore, even though by knowing what form of work is done HR during recovery may be predictable, the reverse is not at this time possible.

What may be true is that the slope of the HR recovery line may be indicative of the intensity of exercise. What needs to be investigated is many different combinations of steady rate and non-steady rate work to see if such a relationship is discernable.

Recommendations

In the event a similar study is carried out in the future, there are certain additions which may be incorporated.
These recommendations are offered with the hope that they will aid future investigators to better answer the questions raised by the present study.

The first suggestion is that without changing the protocol of the study it should be done again and information concerning blood lactic acid should be obtained. By using a scalp vein technique, the concentration of blood lactic acid during and after exercise can be determined. This evidence would greatly aid in our understanding of the significance of the smaller oxygen deficit in condition II (H,L).

It would also be of interest to do a study using different levels of high intensity and low intensity work. There may be an optimal level of high intensity work at which to start an exercise.

A study which investigated the effect of crank speed could also be performed. The differences between steady rate work and non-steady rate work may differ depending on the crank speed used.

Another aspect which merits further study is the way the performer views the task. Most subjects have preconceived notions as to how exercise should be performed. They may view one of the conditions as more difficult than the other conditions. It would be interesting to determine if
any relationship exists between these subjective feelings the performer has concerning the task and that subject's physiological response to it.
Appendix A

Total Work
<table>
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Table 7
Work in $10^3$ Kilopondmeters/Minute
Appendix B

Total Oxygen Deficit
Table 8
Total Oxygen Deficit in Liters

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<tr>
<th>Subject</th>
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</table>
Appendix C

Oxygen Consumption
Figure 1

Oxygen Uptake vs. Time
Appendix D

Oxygen Consumption Compared to Work Rate
Figure 2
Oxygen Uptake Compared to Work Rate
Condition I
Figure 3
Oxygen Uptake Compared to Work Rate
Condition II
Figure 4
Oxygen Uptake Compared to Work Rate
Condition III
Figure 5
Oxygen Uptake Compared to Work Rate
Condition IV
Figure 6
Oxygen Uptake Compared to Work Rate
Condition V
Appendix E
Heart Rate
Figure 7

Heart Rate vs. Time
Appendix F

Calculation of $\dot{V}O_2$
The following equation was used to calculate $\dot{V}_{ESTPD}$

$$\dot{V}_{ESTPD} = \dot{V}_I \cdot \frac{P_B - (P_W \times RH) \times \frac{273}{T + 273}}{760}$$

where

- $\dot{V}_{ESTPD}$ = ventilation in liters/min
- $\dot{V}_I$ = liters of air inspired/min
- $P_B$ = ambient barometric pressure
- RH = ambient relative humidity
- T = ambient temperature in degrees celcius

The following equation was used to calculate $\dot{V}_{O_2}$

$$\dot{V}_{O_2STPD} = \dot{V}_{ESTPD} \times ((1 - (F_{E,O_2} + F_{E,CO_2})) \times .265) - F_{E,O_2}$$

where

- $\dot{V}_{O_2STPD}$ = liters of oxygen consumed/min
- $F_{E,O_2}$ = fractional concentration of oxygen in the expired air
- $F_{E,CO_2}$ = fractional concentration of carbon dioxide in the expired air
Appendix G

Total Oxygen Cost
Table 9

Oxygen Cost in Liters

<table>
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</tr>
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<td>3.21</td>
</tr>
</tbody>
</table>
Appendix H

Use of a Regression Line to Estimate Oxygen Cost of 800 and 1400 Kpm of Work for One Subject
Figure 8

$\dot{V}O_2$ vs. Work

$\dot{V}O_2$ in liters per minute

Work in Kpm
List of References


