THE RELATION OF OXYGEN INTAKE AND SPEED IN COMPETITION CYCLING AND COMPARATIVE OBSERVATIONS ON THE BICYCLE ERGOMETER

BY L. G. C. E. PUGH

From the Laboratory for Field Physiology, National Institute for Medical Research, Holly Hill, London, N.W. 3

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SUMMARY

1. The relation of $\dot{V}_{O_2}$ and speed was determined on six competition cyclists riding at speeds ranging from 12 km/hr to 41 km/hr on the runway of an airfield. Comparative measurements were made on the bicycle ergometer to determine the corresponding work rates, and from this information rolling resistance and air resistance were derived.

2. $\dot{V}_{O_2}$ was a curvilinear function of cycling speed, and increased from 0·88 l./min at 12·5 km/hr to 5·12 l./min at 41 km/hr, mean body weight being 72·9 kg.

3. On the ergometer, $\dot{V}_{O_2}$ was a linear function of work rate; maximum values up to 5·1 l./min (74·4 ml./kg min) and work rates up to 425 W (2600 kg m/min) were observed.

4. Data are presented on the relation of pedal frequency and speed in cycling, and on the relation of mechanical efficiency and pedal frequency, as determined on the ergometer.

5. The estimated rolling resistance for four subjects was 0·71 kg f. The drag coefficient was 0·79 and the drag area 0·33 m². The values agreed well with results obtained by other methods.

6. The energy expenditure (power developed) in cycling increased approximately as the square of the speed, and not as the cube of the speed as expected. This was explained by the varying contribution of rolling resistance and air resistance to over-all resistance to motion at different speeds.

INTRODUCTION

No systematic study of $O_2$ intake and speed in cycling appears to have been made since the time of Zuntz. Zuntz (1899) measured $O_2$ intake at three speeds, the highest $O_2$ intake being 2·5 l./min at 21 km/hr (5·8 m/sec). Others have measured $O_2$ intakes at one or two speeds in connexion with
the energy cost of daily activities (Dill, Seed & Marzulli, 1954; Edholm, Fletcher, Widdowson & McCance, 1955; Garry, Passmore, Warnaock & Durnin, 1955; Malhotra, RamaSwamy & Ray, 1962; Adams, 1967). All these studies were made on subjects riding heavy touring bicycles in an upright posture. Recently Brooks & Davies (1973) have contributed data on racing cyclists riding at 36-8 km/hr.

Estimates of power output and energy expenditure of competition cyclists have been made from observations of tractive resistance (Chandler & Chandler, 1910) and from estimates of rolling resistance and air resistance (Whitt, 1971). Nonweiler (1956) measured the drag area (see below) of competition cyclists suspended on their machines in a wind tunnel.

The present investigation was undertaken as part of a programme to provide basic data on the $O_2$ intake/speed relation in various activities over a wider range of speeds than has previously been attempted.

Respiratory observations were made on subjects riding competition bicycles on the runway of a disused airfield. Observations were also made on the same subjects cycling on an ergometer with a competition frame. The total force opposing motion in cycling and its components – rolling resistance and air resistance – were estimated by comparing work rates and speeds at equal $O_2$ intakes.

METHODS

The observations were made on the runway at the Handley Page aerodrome, Radlett, in conditions of low air movement. One professional and five amateur cyclists took part (Table 1). Their bicycles, which had either 10 or 12 gears, weighed approximately 10 kg and were fitted with practice tyres weighing approximately 250 g and inflated to 5-6-7.0 kg/cm² (80–100 Lb./sq.in.). They wore their normal racing clothing consisting of cotton vest and shorts. The tarmac runway, which was approximately 3 km long, had a loop at one end and a wide open space for turning at the other: it was therefore possible to ride up and down the runway, maintaining a constant speed. The subjects were timed in both directions over a measured kilometre. They selected their own pedal frequencies and gearing.

The respiratory apparatus was carried in a saloon car equipped with a boom, which was fitted to the roof-rack level with the top of the windscreen. The distance between the cyclist and the side of the car was 1·8 m. The respiratory apparatus consisted of a low-resistance valve unit suspended from the boom, a 3 m length of vacuum-cleaner tubing (30 mm internal diameter) and a 300 l. plastic bag.

Expired gas was collected first on the up-run and then on the down-run. The subjects cycled at a given speed for at least 5 min before the first gas collection, and for a minimum of 90 sec before the second gas collection. At speeds up to 30 km/hr (8 m/sec) the two gas samples were collected in the same bag. At higher speeds separate bags were used. The expired gas was passed through a calibrated dry gas-meter, shaded from the sun, and analysed concurrently on a Lloyd gas analyser (Lloyd, 1958). Wind velocity was recorded with a cup anemometer at the side of the track. The component parallel with the track was calculated, for each cycling speed, from the total air movement and wind direction. This was referred to as effective air velocity ($v$). Air temperature was measured with a sling hygrometer.
Posture and projected area. At the fastest speeds the subjects rode with their hands on the 'grips' of the handlebars and their backs nearly horizontal. This was referred to as the 'fully dropped' posture. At intermediate speeds they rode with the hands on the curve of the handlebars. At very slow speeds they rode in a more upright posture with the hands resting on top of the handlebars and the arms straight. The projected areas of the subjects in these three postures were determined from photographs of the subjects riding towards the camera at slow, medium and fast speeds. The height and width of the handlebars served as reference dimensions. Enlarged prints of the subjects and their machines were cut out and weighed against rectangles cut to the reference dimensions from the same paper.

Table 1. Particulars of the subjects. Results in parentheses were submaximal

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>$\dot{V}_2 \max.$ (ml/kg l./min)</th>
<th>$\dot{w} \max.$ (kg m/min)</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>W.H.</td>
<td>21</td>
<td>186-0</td>
<td>72-19</td>
<td>5-31</td>
<td>74-4</td>
<td>2538</td>
</tr>
<tr>
<td>M.C.</td>
<td>25</td>
<td>171-5</td>
<td>68-80</td>
<td>4-18</td>
<td>69-2</td>
<td>1980</td>
</tr>
<tr>
<td>S.B.</td>
<td>25</td>
<td>176-0</td>
<td>66-68</td>
<td>4-11</td>
<td>61-4</td>
<td>1957</td>
</tr>
<tr>
<td>D.D.</td>
<td>25</td>
<td>184-2</td>
<td>73-03</td>
<td>4-32</td>
<td>57-3</td>
<td>1859</td>
</tr>
<tr>
<td>G.C.</td>
<td>35</td>
<td>185-0</td>
<td>80-01</td>
<td>(4-41)</td>
<td>(55-1)</td>
<td>(2122)</td>
</tr>
<tr>
<td>R.A.</td>
<td>31</td>
<td>188-0</td>
<td>75-50</td>
<td>5-24</td>
<td>68-3</td>
<td>2601</td>
</tr>
<tr>
<td>Mean</td>
<td>27</td>
<td>181-8</td>
<td>72-87</td>
<td>4-04</td>
<td>64-3</td>
<td>2187</td>
</tr>
</tbody>
</table>

Ergometer exercise. Later in the competition season, and within 2–4 weeks of the cycling experiments, the subjects attended the laboratory for exercise tests on the ergometer. The ergometer was of the Von Döbeln (1954) type. It had a competition frame and saddle, but was fitted with roadster (straight) handlebars instead of fully dropped handlebars. The respiratory exchanges and heart rates were observed at rest (sitting on the ergometer in the intermediate posture) and at five to six work rates up to the maximum that the subjects could maintain for 4–5 min. Before the final work rate the subjects rested for about 30 min. Pedal frequencies were chosen by the subjects themselves during preliminary practice, as was the load for the final work rate. Subjects pedalled at the same frequency at all work rates, keeping time to a metronome. The total number of pedal revolutions at each work rate was registered on a cyclometer. The load was controlled throughout by an observer.

The effect of pedal frequency on mechanical efficiency was studied in one subject, G.C., in four experiments using various combinations of pedal frequency and work rate so as to confound day-to-day variation. Mechanical efficiency ($\epsilon$) was calculated by the formula

$$\epsilon = \dot{w}/\text{net } O_2 \text{ intake } \times 4.9 \times 427,$$

where $\dot{w}$ was mechanical work performed in kg m/min, 4.9 was the thermal equivalent of oxygen in kcal/l., 427 was the mechanical equivalent of heat in kg m/kcal. Net $O_2$ intake in l./min was calculated as observed $O_2$ intake minus resting $O_2$ intake in l./min.

Derivation of rolling resistance and air resistance. The resistance to motion in cycling is equal to the sum of rolling resistance ($R_r$), frictional resistance ($R_f$) and air resistance ($R_a$). $R_t$ in competition bicycles is small and can be included under $R_a$, so that

$$R = R_r + R_a.$$ (1)
$R_r$ is a constant depending on road surface, gross weight and characteristics of the tyres, including inflation pressure (Whitt, 1971). $R_r$ varies as the square of air velocity which, in calm conditions, can be taken as the cyclist’s speed ($\dot{s}$). Thus

$$R_r = b\dot{s}^2,$$  \hspace{1cm} (2)

in which $b$ is Eiffel’s coefficient of air resistance.

Values of $R$, $R_r$, $b$ and $R_r$ are derived from the experimental results by the following procedure.

Graphs were constructed relating $O_2$ intake ($\dot{V}_{O_2}$) to cycling speed ($\dot{s}$), and $O_2$ intake ($\dot{V}_{O_2}$) to work rate ($\dot{w}$) on the ergometer. Values of $\dot{w}$ and $\dot{s}$ at equal $\dot{V}_{O_2}$ were read off, and $\dot{w}$ was divided by $\dot{s}$ to obtain the total force opposing motion ($R$). $R$ was then plotted against $\dot{s}^2$, which yielded a straight-line relation

$$R = R_r + b\dot{s}^2,$$  \hspace{1cm} (3)

the slope of which was the air resistance coefficient ($b$) and the intercept the rolling resistance ($R_r$). The values of $R$ used in constructing graphs of eqn. (3) were calculated using interpolated $\dot{s}$ at measured $\dot{w}$ and vice versa. Straight lines were fitted to these results by the method of least squares.

Engineers describe the relation of air resistance or drag ($D$) to wind velocity ($v$) in terms of a dimensionless group, the drag coefficient ($C_D$); or, when the projected area is not known, in terms of the drag area ($A_D$) in square metres.

The drag coefficient ($C_D$) is the ratio of drag ($D$) to the dynamic air pressure, and is defined by the equation

$$C_D = \frac{D}{0.5\rho A_p v^2},$$  \hspace{1cm} (4)

in which $D$ is drag in kilogrammes force, $\rho$ is air density in kg f sec$^2$/m$^4$, $A_p$ is the projected area in m$^2$ and $v$ is air velocity in m/sec. Since the term ‘drag’ is synonymous with the term ‘air resistance’

$$D = b\dot{s}^2,$$  \hspace{1cm} (5)

and for cycling in calm air

$$C_D = \frac{b}{0.5\rho A_p},$$  \hspace{1cm} (6)

for $v$ can be taken as equal to $\dot{s}$. At sea level atmospheric pressure (760 mmHg) and temperature 15° C the value of $\rho$ is 0.123, so that

$$C_D = \frac{b}{0.0625 A_p}$$  \hspace{1cm} (7)

(at 20° C and 760 mmHg, $\rho = 0.1205$ kg sec$^2$/m$^4$). The drag area, $A_D$, is the value of $A_p$ for $C_D = 1$. Hence

$$A_D = \frac{b}{0.0625} \text{ in m}^2.$$  \hspace{1cm} (8)

For a more detailed treatment of this subject from a physiological point of view, the reader is referred to a previous paper on wind resistance in walking and running (Pugh, 1971).

**RESULTS**

**Oxygen intake and energy expenditure in cycling.** Fig. 1a and b show the relation of $O_2$ intake ($\dot{V}_{O_2}$) and speed ($\dot{s}$) for six competition cyclists. Each plotted value is a single result. Polynomial equations were fitted by the
method of least squares. \( \dot{V}_O_2 \) is expressed in l/min in Fig. 1a and in ml. kg/min in Fig. 1b. The scatter was reduced by plotting \( \dot{V}_O_2 \) in terms of body weight. This was to be expected since both air resistance and rolling resistance in cycling are functions of body size.

Fig. 1. Relation of oxygen intake and cycling speed for six competition cyclists.

Fig. 2. Relation of net energy expenditure and cycling speed for six competition cyclists. Inset is a plot of energy expenditure against the square of speed.
In Fig. 2 the results are expressed in terms of net energy expenditure ($\bar{E}$) in W/kg and g cal/kg sec with speed in m/sec. The resting values of $\bar{V}_O_2$ used in calculating net energy expenditure were taken from the ergometer experiments. Also shown is a plot of $\bar{E}$ against $s^2$, demonstrating that $\bar{E}$ increased approximately as the square of the speed.

Pedal frequency. Fig. 3 shows the relation of pedal frequency and road speed for four subjects. The frequencies were averages based on the number of revolutions counted over approximately 1 min. At road speeds under 5 m/sec the values may be unreliable owing to excessively light pedal pressures and consequent free-wheeling. It is seen that pedal frequency was a linear function of road speed for all subjects.

![Fig. 3. Relation of pedal frequency and cycling speed.](image)

Projected areas ($A_p$). The mean projected areas for the 'fully dropped', intermediate and upright postures were respectively 0·42, 0·46 and 0·47 m², or 0·21, 0·23 and 0·24 m² per square metre of whole body surface area. The variation in $A_p$ with the phase of leg movement was small.

Effect of wind. Three subjects, R.A., D.D. and W.H., were studied on exceptionally calm days, the effective wind velocities (v) being 0·36, 0·38 and 1·37 m/sec respectively. Two subjects, M.C. and S.B., were studied on days with perceptible wind, the effective wind velocities being 3·47 and 2·99 m/sec respectively. Wind velocity in the case of subject G.C.
was not measured, but was small. The effect of wind at given road speeds is illustrated in Fig. 4, which shows the $\dot{V}O_2$ observed on the up-run and down-run for two subjects, one of whom was observed in calm conditions and the other in the presence of perceptible wind. Similar results were obtained in other subjects. Even in calm conditions there was a difference in $\dot{V}O_2$ of about 0.5 l./min between the up-run and down-run. It was not established for certain whether this was due to the presence of a very slight gradient in the runway, or to variation in air movement, or both.

**Fig. 4.** Effect of wind on oxygen intake in cycling. The numbers indicate mean effective wind velocity in m/sec.

**Ergometer exercise.** The results for all subjects are shown in Fig. 5. Each plotted value is a single result. The line was fitted by the method of least squares. The equation of the line was $y = 0.019x + 0.51$. No attempt was made to demonstrate a plateau of $\dot{V}O_2$ by imposing supra-maximal loads. However, the values shown in Table 1 were considered maximal for these subjects and are probably representative of cyclists of club standard. $\dot{V}O_2$ up to 80 ml./kg min have been observed in international-class cyclists (Saltin & Astrand, 1967).

Pedal frequencies on the ergometer and pedal frequencies in cycling are compared in Fig. 6. It is seen that the frequencies were in the same range at $\dot{V}O_2$ of 21 l./min and over, but at $\dot{V}O_2$ less than 21 l./min the frequencies were considerably slower in cycling than on the ergometer.

**Mechanical efficiency.** Fig. 7 shows the relation of mechanical efficiency and work rate at various pedal frequencies. The values were nearly constant at work rates from 145 to 330 W (900–2000 kg m/min). The mean values within this range were 0.25 at pedal frequency 51–54/min and
Fig. 5. Relation of oxygen intake and work rate on the ergometer. Symbols as in Fig. 1.

Fig. 6. Comparison of pedal frequencies in cycling and ergometer exercise.
74–77/min, and 0.22 at pedal frequency 86–88/min. At work rates less than 145 W (900 kg m/min) efficiency decreased progressively at these higher frequencies, but did not change significantly at the lowest frequency.

**Rolling resistance and air resistance.** The relation of $F$ and $\dot{s}^2$ for four subjects is shown in Fig. 8. The regression lines were calculated by the method of least squares. Values of $\dot{w}$ less than 900 kg m/min and values of $\dot{s}$ less than 5 m/sec were omitted owing to possible inequalities of mechanical efficiency due to differences of pedal frequency between cycling and ergometer exercise at low work intensity. Values of $R_r$, $A_D$ and $C_D$ derived from the slopes ($b$) and intercepts ($R_t$) of the above lines are contained in

![Fig. 7. Mechanical efficiency at various work rates and pedal frequencies. Subject G.C. Numbers indicate pedal frequencies.](image)

### Table 2. Estimates of rolling resistance ($R_r$), drag coefficient ($C_D$) and drag area ($A_D$) for four subjects, with observed projected areas for the 'fully dropped' position ($A_p$), and the values of Eiffel's coefficient ($b$) from which $C_D$ and $A_D$ were calculated

<table>
<thead>
<tr>
<th>Subject</th>
<th>$R_r$ (kg f)</th>
<th>$C_D$</th>
<th>$A_D$ (m²)</th>
<th>$A_p$ (m²)</th>
<th>$b$ (kg f $\dot{s}^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D.D.</td>
<td>0.61</td>
<td>0.78</td>
<td>0.31</td>
<td>0.40</td>
<td>0.0193</td>
</tr>
<tr>
<td>R.A.</td>
<td>0.71</td>
<td>0.79</td>
<td>0.35</td>
<td>0.44</td>
<td>0.0217</td>
</tr>
<tr>
<td>W.H.</td>
<td>0.73</td>
<td>0.83</td>
<td>0.33</td>
<td>0.40</td>
<td>0.0204</td>
</tr>
<tr>
<td>G.C.</td>
<td>0.80</td>
<td>0.77</td>
<td>0.32</td>
<td>0.44</td>
<td>0.0211</td>
</tr>
<tr>
<td>Mean</td>
<td>0.71</td>
<td>0.79</td>
<td>0.33</td>
<td>0.42</td>
<td>0.0206</td>
</tr>
</tbody>
</table>
Fig. 8. a, Relation of oxygen intake and speed, and oxygen intake and work rate, for four subjects; b, relation of total resistance to motion ($R$) and the square of road speed ($v^2$) estimated from the results shown in a.
Table 2. The Table contains results for four subjects observed at wind velocities less than 1·5 m/sec. The mean values of $C_D$ and $A_D$ were respectively 0·79 and 0·33. The mean value of $R_r$ was 0·71 kg. A higher $C_D$ of 0·94 was obtained in a fifth subject, M.C., who was observed at an effective wind velocity of 3·47 m/sec, $R_r$ being 0·6 kg.

**DISCUSSION**

The results obtained at Radlett were surprisingly consistent in view of the fact that there was always a certain amount of air movement on the runway. The light breeze present on some occasions varied from minute to minute, both in direction and intensity, and could not be evaluated with enough precision to make worthwhile correction of $V_{O_2}$ for wind. In general $V_{O_2}$, at given $s$ and zero $v$, will be over-estimated by averaging $V_{O_2}$ for runs in opposite directions. For it can be shown that $F_a$ will vary not as $s$ but as $(s^2 + v^2)$. This effect is not, however, serious at $v < 2$ m/sec. For example, at $v = 2$ m/sec $V_{O_2}$ will be over-estimated by 6 per cent at a cycling speed of 6 m/sec and by 3 per cent at a speed of 10 m/sec. On the other hand, at $v = 4$ m/sec $V_{O_2}$ would be over-estimated by 24 and 12 per cent respectively. The assumption that the retarding effect of wind is proportional to the square of the component parallel with the track is not entirely justified, since cyclists are quite sensitive to cross-winds. However, at the low air speeds prevailing in these experiments, the effect of cross-wind is likely to have been small.

The results show that the rate of energy expenditure or power developed in cycling increases approximately as the square of air resistance, and not as the cube of resistance as might be expected from the fact that air resistance varies as the square of air velocity. This finding confirms some early results by Chandler & Chandler (1910), who measured tractive resistance on pairs of cyclists towing each other with a cord and spring balance. The explanation lies in the relative preponderance of the two components of tractive resistance at different speeds. At speeds less than 8 m/sec the power required to overcome rolling resistance (which increases directly with speed) is the major factor. At speeds over 8 m/sec the power required to overcome air resistance (which increases as the cube of speed) is dominant.

**Rolling resistance and air resistance.** The agreement with direct measurements of drag on cyclists suspended in a wind tunnel (Nonweiler, 1956), and with rolling resistance ($R_r$) estimated from the formula cited by Whitt (1971) is surprisingly good. Nonweiler found a mean value of 0·31 m$^2$ for $A_D$ in the ‘racing’ posture and 0·37 for the ‘touring’ posture on four subjects of average weight (71·5 kg) and height (178 cm). He gave a value
of 0.93 for $C_D$, using an assumed value of 0.33 m$^2$ for $A_p$ in the 'racing' (i.e. 'fully dropped') posture.

The mean value of 0.71 kg for rolling resistance was the same as the value predicted from a formula given by Whitt (1971) based on gross weight and tyre-inflation pressure. Values of 0.7-0.8 kg were observed in some crude towing experiments at Radlett. On the other hand, values of around 0.25 kg were observed with the subjects riding their bicycles on the treadmill at Hampstead, which had a polished linoleum belt running over boards. This explained the fact that cyclists can maintain higher speeds on indoor tracks with smooth surfaces than they can on roads, the differences being of the order of 5 km/hr.

The derivation of $R_r$ and $R_a$ by comparing $w$ and $\dot{V}_o$ at equal $\dot{V}_o$, rests on the assumption that the mechanical efficiency of cycling was the same as that of ergometer exercise at each level of $\dot{V}_o$. The agreement with results obtained by other methods suggests that this condition was adequately met. However, the investigation can be criticized on the grounds that the pedal frequencies were not matched and that the ergometer did not have dropped handlebars. The cyclists themselves did not consider that the lack of dropped handlebars affected their style significantly, since they could easily imitate the 'fully dropped' posture by increased flexion of the arms at the elbow. With regard to pedal frequency, the results in Fig. 5 suggest that there may have been disparities in efficiency at low $\dot{V}_o$, due to the different pedal frequencies; but this difficulty was avoided by not using results at the low end of the $\dot{V}_o$ range in deriving $R_r$ and $R_a$.

**Mechanical efficiency.** The uniformity of mechanical efficiency over a wide range of work rates and frequencies confirms the results of Bannister & Jackson (1967) on an Olympic oarsman. Eckermann & Millahn (1967) reported greater variation in untrained subjects. The constancy of efficiency down to 50 W at 50 pedal rev/min agrees with the results of Åstrand (1952) and I. Åstrand (1960). The finding that efficiency at higher pedal frequencies declined progressively at work rates below 150 W appears to be new.

**Posture.** The change in posture at various cycling speeds is another factor that might influence the relation of $F$ and $\dot{s}$, since the drag is proportional to projected area. However, correction of $F$ to constant $A_p$ did not significantly affect the results, the reason being that at high work rates, when the effect of $R_a$ on $\dot{V}_o$ is large, $A_p$ was minimal since the cyclists were in the fully dropped posture; on the other hand at low speed, when $A_p$ was maximal, the contribution of $R_a$ to total resistance was small.

**Practical aspects.** The 5-min maximum work rate of 450 W (2600 kg m/min) of subject R.A., a professional cyclist, was equivalent to a
power output of 0.57 h.p. The $V_{O_2}$ max. data of Saltin & Åstrand (1967), as well as the record performances mentioned below, suggest that world-class professional cyclists may be capable of maintaining a power output of 0.57 h.p. for up to an hour. Owing to the effect of air resistance, groups of cyclists can ride significantly faster than unaccompanied riders. This is done by changing leaders every 10–20 sec. The leader rides at a speed exceeding his $V_{O_2}$max. and drops back to recover in the wake of other riders. Another consequence of the effect of air resistance in cycling is that faster times can be made in competitions at altitude, in spite of oxygen lack, for air density – and therefore air resistance – decreases with altitude in direct proportion to atmospheric pressure. The present world record of 49.43 km for 1 hr of unaccompanied cycling was set up in Mexico City at an altitude of 2230 m (atm pressure 580 torr). The nearest comparable result for sea level is 48.09 km, which was the European record set up in Rome in 1967.

Grateful acknowledgement is made to the subjects of these experiments, and to Dr J. R. Brotherhood, Mr J. A. Crisp and Mrs B. Molloy, who collaborated in carrying out the experiments.

REFERENCES


