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THE INFLUENCE OF WIND RESISTANCE IN RUNNING AND WALKING AND THE MECHANICAL EFFICIENCY OF WORK AGAINST HORIZONTAL OR VERTICAL FORCES

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. O_2 intakes were determined on subjects running and walking at various constant speeds, (*a*) against wind of up to 18·5 m/sec (37 knots) in velocity, and (*b*) on gradients ranging from 2 to 8%.

2. In running and walking against wind, O_2 intakes increased as the square of wind velocity.

3. In running on gradients the relation of O_2 intake and lifting work was linear and independent of speed. In walking on gradients the relation was linear at work rates above 300 kg m/min, but curvilinear at lower work rates.

4. In a 65 kg athlete running at 4·45 m/sec (marathon speed) $\dot{V}_{O_2}$ increased from 3·0 l./min with minimal wind to 5·0 l./min at a wind velocity of 18·5 m/sec. The corresponding values for a 75 kg subject walking at 1·25 m/sec were 0·8 l./min with minimal wind and 3·1 l./min at a wind velocity of 18·5 m/sec.

5. Direct measurements of wind pressure on shapes of similar area to one of the subjects yielded higher values than those predicted from the relation of wind velocity and lifting work at equal O_2 intakes. Horizontal work against wind was more efficient than vertical work against gravity.

6. The energy cost of overcoming air resistance in track running may be 7·5% of the total energy cost at middle distance speed and 13% at sprint speed. Running 1 m behind another runner virtually eliminated air resistance and reduced $\dot{V}_{O_2}$ by 6·5% at middle distance speed.

INTRODUCTION

The influence of wind resistance in running and walking, and the mechanical efficiency of work against horizontal or vertical forces has been discussed in several recent papers on the energetics of athletic performance

(Lloyd, 1967; Margaria, 1968*a*; Pugh, 1970). Lloyd and Margaria made use of Hill's (1927) equation for air resistance and wind velocity, which was based on experiments with a model in a wind tunnel. But in order to calculate the energy expenditure or power developed by a runner in overcoming air resistance from data on wind pressure, it is necessary to know the mechanical efficiency of the external work done, and this cannot be determined with models. Margaria (1968*a*) got over this difficulty by assuming that the efficiency of work against the horizontal force of air resistance was the same as the efficiency of work against the vertically acting force of gravity, which he had determined in earlier experiments on gradient exercise. Both Margaria (1968*a*) and Lloyd (1967) postulated a value of 0·25 for the efficiency of work against wind. Lloyd, however, pointed out in a footnote that a value of 0·50 for efficiency fitted the record data better than a value of 0·25. Pugh (1970) avoided this issue by estimating energy expenditure from observations of the O_2 intake ($\dot{V}_{O_2}$) of an athlete running on a treadmill at a constant speed against wind of varying velocity. He found that the energy cost of overcoming air resistance was about 8 % of the total energy cost of outdoor running at a speed of 6 m/sec, which is representative of 5000 and 10,000 m races, and may be about 16 % of the total energy cost in sprinting 100 m in 10 sec.

Air resistance is also of interest in walking, but from another point of view. At ordinary walking speeds in calm air its effect is minimal; but strong winds can greatly increase the effort of walking. There is evidence that the increased effort of fighting gale force winds is an important cause of exhaustion leading to hypothermia accidents among walkers and climbers in the hills and on the moorlands of Britain (Pugh, 1966).

The purpose of the investigation herein reported has been to confirm and extend the previous work (Pugh, 1970) by observing the oxygen cost of walking against wind, as well as running against wind; and secondly, to determine the mechanical efficiency of work against wind and to compare it with the efficiency of work against gravity.

METHODS

Definitions and calculations

Wind resistance and drag. Hill (1927) stated that the air resistance R to a runner was equal to 0·056 $v^2 A_r$ where R is in kilogrammes, v is in metres per second and A_r in square metres is the area of the runner projected in a plane perpendicular to the direction of motion. The constant 0·056 incorporated a term for air density. With air density ρ the formula becomes

$$R = 0{\cdot}45\,\rho v^2 A_r.$$

Although wind resistance was the term originally used by Eiffel (1909) to denote the pressure exerted on solid objects by wind of given velocity, the term drag (D) is preferred in aerodynamic applications.

Engineers describe the relation of drag (D) and wind velocity (v) in terms of a dimensionless group, the drag coefficient (C_D). The drag coefficient is the ratio of drag (D) to the dynamic pressure (q) of a moving air stream and is defined by the equation

$$C_D = \frac{D}{qA_p}, \tag{1}$$

where A_p is the projected area. The dynamic pressure q, which is equivalent to the kinetic energy per unit volume of a moving solid body, is defined by the equation

$$q = 0{\cdot}5\,\rho v^2, \tag{2}$$

where ρ is the density of the air in kilogrammes per cubic metre. The drag coefficient for a runner according to Hill's result would be approximately 0·9.

Reynold's number. The coefficient of drag is a function of another dimensionless group, the Reynold's number (R). This is defined by the equation

$$R = \frac{vl}{\nu}, \tag{3}$$

where ν is the kinematic viscosity of the air at given temperature and pressure and l is a representative dimension of the body such as diameter or length. In practical applications the area A_p is sometimes substituted for l, in which case it is usual to divide by another dimension such as height in order to retain a non-dimensional group.

Kinematic viscosity is the ratio of air viscosity (μ) to air density (ρ) so that

$$\nu = \frac{\mu}{\rho}. \tag{4}$$

Values of ρ, μ and ν for various temperatures are shown in Table 1.

The relation of C_D and R for a circular cylinder which the human body is stated to resemble in its aerodynamic characteristics (Hoerner, 1965*a*) is shown in Fig. 1. In this application R is related to diameter. It is seen that C_D is fairly constant over a range of R values extending from 10^3 to 10^5, and that the values of R within the range of air velocities employed in this investigation occupied the upper end of this range. Above $R = 1 \times 10^5$, C_D falls progressively, reaching a new low level at about $R = 5 \times 10^5$, which is known as the critical Reynold's number (R_{crit}). The fall in C_D as R_{crit} is approached is associated with a change in the characteristics of the air flow behind the body. This change consists in the break-up of the wake from a more or less orderly system of vortices (Fig. 2) to a completely disordered state of random turbulence. In the presence of this degree of turbulence the boundary layer of air clinging to the sides of the body extends further round the circumference causing the wake to narrow, thereby reducing drag. This condition is known as fully developed turbulence. The zone of more or less constant C_D is the transitional zone, and the zone below this where C_D is a linear function of R is the zone of laminar air flow.

Units. In this investigation metric units have been used instead of the foot pound system commonly used by British and American engineers.

Dynamic pressure (q) is in kg/m^2. Drag D is in kg. Air density ρ is in kg sec^2/m^4. Air viscosity μ is kg sec/m^2. Kinematic viscosity ν is in m^2/sec. Air velocity v is in m/sec. The kilogramme (kg) is the kilogramme force.

Work done against wind resistance. The external work rate $\dot{\omega}$ of a man walking on a treadmill at a speed $\dot{s}$ against a wind of velocity v, which exerts on his body a force P is given by

$$\dot{\omega} = P\dot{s} \tag{5}$$

and since

$$P \propto v^2,$$

$$\dot{\omega} \propto \dot{s}v^2. \tag{6}$$

TABLE 1. Density, viscosity and kinematic viscosity of air at various temperatures and at 760 mm Hg pressure

Temp. (°C)	Density ρ (kg sec²/m⁴)	Viscosity $\mu \times 10^6$ (kg sec/m²)	Kinematic viscosity $v \times 10^6$ (m²/sec)
0	0·132	1·709	12·95
10	0·127	1·767	13·91
20	0·123	1·831	14·89
40	0·114	1·948	17·09

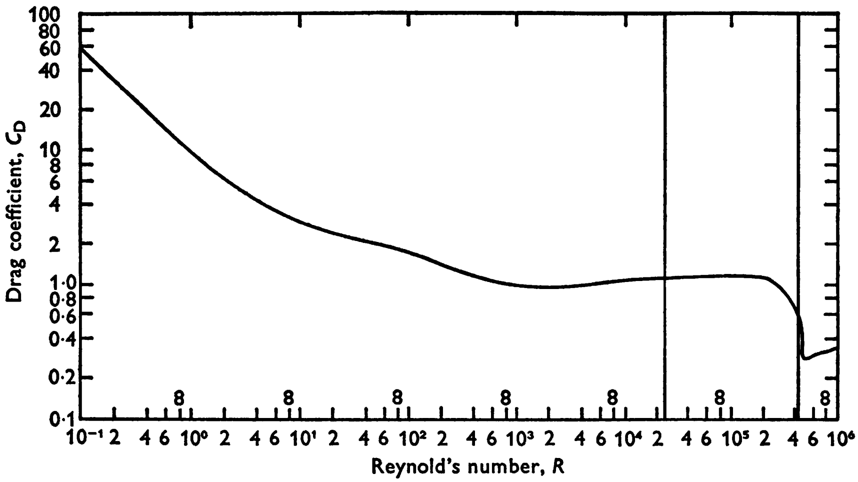


Fig. 1. The relation of the drag coefficient (C_D) and the Reynold's number (R) for a circular cylinder with its axis normal to the direction of air flow (redrawn from Schlichting, 1968). The vertical lines show limits of R over a range of wind velocities extending from 1·5 to 18·5 m/sec.

Rate of energy expenditure (*power developed*). The rate of energy expenditure (E), or power developed, in performing work against wind at a rate $\dot{\omega}$ is given by the expression

$$E = \frac{\dot{\omega}}{ke},$$

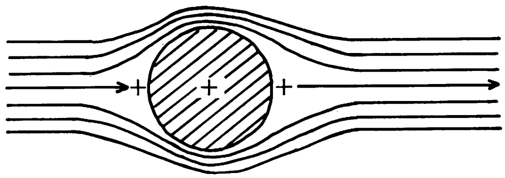
where e is the mechanical efficiency and k is a constant converting the terms to thermal units. Hence

$$E = \frac{P\dot{s}}{ke}. \tag{7}$$

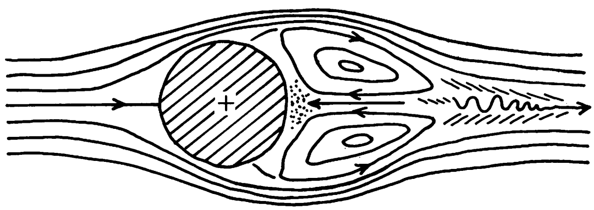
For exercise in the steady state E can be expressed in terms of the concurrent oxygen intake in ml./sec: and with $P\dot{s}$ in kg m/sec, k is equal to

$$\frac{0{\cdot}0049}{0{\cdot}00235} = \frac{1}{2{\cdot}09},$$

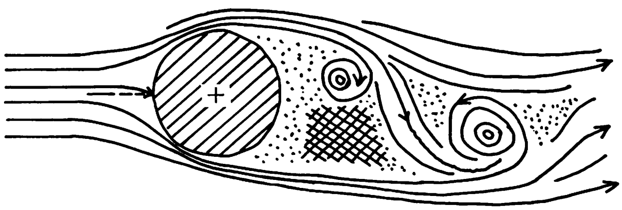
where 0·0049 is the thermal equivalent of oxygen in kcal/ml. at r = 0·9, and 0·00235 is the thermal equivalent of mechanical work in kcal/kgm.



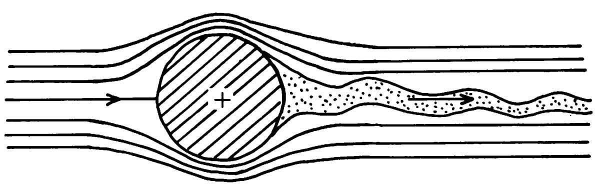
(1) Flow pattern of circular cylinder in non-viscous flow; no drag



(2) Cylinder at Reynold's numbers in the order of 40; $C_D \approx 4{\cdot}0$



(3) Cylinder between $R_d = 10^4$ and 10^5; vortex street with $C_D = 1{\cdot}2$



(4) Cylinder above critical Reynold's number with $C_D = 0{\cdot}3$

Fig. 2. Diagrammatic representation of the air flow patterns round a circular cylinder at various Reynold's number. Note the reduction of drag (C_D) above the critical Reynold's number (redrawn from Hoerner, S. F., 1965).

Writing $\Delta\dot{V}_{O_2}$ for the extra O_2 intake due to the presence of wind, i.e. observed $\dot{V}_{O_2}$ at wind velocity v minus $\dot{V}_{O_2}$ at the same treadmill speed ($\dot{s}$) without wind we get

$$\Delta\dot{V}_{O_2} = \frac{\dot{\omega}}{2{\cdot}09e}, \tag{8}$$

or

$$\Delta\dot{V}_{O_2} = \frac{P\dot{s}}{2{\cdot}09e}.$$

Hence

$$e = \frac{P\dot{s}}{2{\cdot}09\Delta\dot{V}_{O_2}}. \tag{9}$$

Rate of work against gravity ($\dot{\omega}'$). By similar reasoning, the rate of work done against the vertical force of gravity by a person running or walking on a treadmill set at a speed $\dot{s}$ and gradient h is equal to

$$\dot{\omega}' = \dot{s}hW, \tag{10}$$

where W is the gross weight raised, and h is the sine of the angle of gradient. The force F exerted against gravity is given by

$$F = \frac{\dot{\omega}'}{\dot{s}} \tag{11}$$

so that (from eqn. (10))

$$F = hW. \tag{12}$$

Taking $\Delta\dot{V}'_{O_2}$ as the difference in $\dot{V}_{O_2}$ between running or walking at a speed $\dot{s}$ on a gradient h, and horizontal running or walking at the same speed, we get

$$\Delta\dot{V}'_{O_2} = \frac{\dot{\omega}'}{2{\cdot}09e'}, \tag{13}$$

and

$$\dot{V}'_{O_2} = \frac{F\dot{s}}{2{\cdot}09e'},$$

hence

$$e' = \frac{F\dot{s}}{2{\cdot}09\Delta\dot{V}'_{O_2}}, \tag{14}$$

where e' is the mechanical efficiency of work against the force of gravity. Equating $\Delta\dot{V}_{O_2}$ and $\Delta\dot{V}'_{O_2}$ in eqns. (9) and (14) and eliminating we get

$$\frac{P\dot{s}}{e} = \frac{F\dot{s}}{e'}$$

so that

$$\frac{P}{F} = \frac{e}{e'}. \tag{15}$$

Apparent efficiency. The mechanical efficiency (e, e') as defined in eqns. (9) and (14) is referred to below as apparent efficiency in order to distinguish it from Margaria's (1968*a*, *b*) usage. Margaria calculated mechanical efficiency as the ratio of external work to net $\dot{V}_{O_2}$, net $\dot{V}_{O_2}$ being the difference between observed $\dot{V}_{O_2}$ and basal $\dot{V}_{O_2}$.

Air resistance expressed as an equivalent gradient. Both Hill (1927) and Margaria (1968*a*) have expressed P in terms of an equivalent gradient. The derivation is as follows:

If we put $\dot{\omega} = \dot{\omega}'$ so that

$$P\dot{s} = h\dot{s}W,$$

$$P = hW, \tag{16}$$

where W is the gross weight and h is the gradient equivalent to P.

Subjects and conditions

Subjects. M. Turner, an international middle and long-distance runner who had taken part in previous investigations (Pugh, 1966, 1970), acted as subject for the running experiments. Three non-athletes accustomed to prolonged physical exertion acted as subjects for the walking experiments. Their physical characteristics are shown in Table 2.

TABLE 2. Physical characteristics of subjects

Subjects		Age (yr)	Weight (kg)	Height (cm)	Surface area (m^2)	Projected area (m^2)	$\dot{V}_{O_2 max}$ l./min	$\dot{V}_{O_2 max}$ ml./kg min
M. Turner	Runner	29	65·0	179·1	1·78	0·478	4·96	76·3
J. Brotherhood	Walker	29	74·7	177·8	1·92	0·600	4·20	56·2
J. Fry	Walker	26	78·8	182·5	2·02	0·625	3·62	45·9
R. Hillier	Walker	29	87·8	184·0	2·14	0·668	3·60	41·0

Climatic chambers. Most of the observations on running against wind were made in the climatic chamber at the Institute of Aviation Medicine (IAM) at Farnborough. In this chamber the fan is down-wind of the treadmill and the air stream is deflected through an angle of 90° by a set of vertical vanes situated 3 m ahead of the treadmill. Wind velocities from 1·5 to 18·5 m/sec (37 knots) are available. The experiments on running and walking on a gradient, and all but one of the experiments on walking against wind were performed in the climatic chamber at Hampstead. In this chamber the fan is ahead of the treadmill and air flows through a wire-mesh screen situated 2 m ahead of the treadmill. The range of wind velocities available is 0·5 to 11·5 m/sec. In both chambers the air flow was turbulent and cup anemometer readings fluctuated within a range of about 1·0 m/sec at high wind velocities. Vane anemometers showed less fluctuation. The observations of $\dot{V}_{O_2}$ were made at the same fan settings in all experiments. The wind velocity was checked several times at each fan setting during each experiment by means of cup and vane anemometers placed at a height chosen to give a representative average air flow. The position of the instruments was selected in the light of a large number of observations at various heights and distances from the walls of the chamber at Hampstead. Comparative measurements of air flow were also made with a Pitotstatic tube.

Projected area. The runner's projected area was measured from photographs taken at Farnborough during running. The method has been described previously (Pugh, 1970). A similar procedure was followed with J.B. who was the subject of the walking experiment at Farnborough. Owing to lack of space ahead of the treadmill at Hampstead, the other subjects were not photographed during walking. Their projected areas were determined from photographs taken in a standing posture outside the chamber. Comparative measurements on J.B. indicated that the average projected area was about 5 % less while walking against wind than in a standing posture in the absence of wind. This was due to the garments being pressed against the surface of the body by the wind; a 5 % correction was therefore applied. There was also a slight diminution of projected area associated with leaning forward against strong winds, but its magnitude could not be determined precisely with the equipment available.

Wind velocity and wind pressure. The relation of wind pressure and wind velocity was established by direct measurement at Hampstead. The method adopted was as follows. Subject J.B. lay on the floor and his outline was drawn on paper. A $\frac{3}{8}''$ plywood board was cut to this shape and its centre of gravity determined. The board was suspended above the treadmill so that the bottom of the board was 2 cm above the belt of the treadmill. The bottom of the board was connected to a calibrated spring-balance by means of a thread passing over a low-friction pulley. The force (F) required to keep the board vertically over a mark on the treadmill was observed at various fan settings and wind velocities. The force (F) exerted at the centre of pressure, which for a board of uniform thickness is also the centre of gravity, was calculated from the relation $F = (l/d)F'$ where F' was the observed force in kg at wind velocity v m/sec, l was the height of the board in metres and d was the distance in metres from the centre of gravity to the point of suspension.

The experiments were repeated with a rectangular board of the same height and surface area, and again with an elliptical cylinder of the same height and projected area. The dimensions of the cylinder were height 179 cm, width 35 cm, maximum antero-posterior diameter 15 cm. The height-to-width ratio was 5:1. According to Hoerner (1965*a*) the human body is aerodynamically similar to a circular cylinder having a height-to-width ratio of between 4 and 7. The characteristics of the elliptical cylinder employed in our experiments may be expected to be similar to those of a circular cylinder (Hoerner, 1965*b*).

Running against wind and running on a gradient. Thirteen experiments on running against wind and running on a gradient were performed. The same procedure was followed in both types of experiments. The subject ran continuously at a constant treadmill speed for periods of up to 75 min; and for a further period of about half-an-hour following a 2 hr break during which he took a light meal and enough fluid to restore his body weight. Each session began with a 15 min control period of running with minimal wind velocity and zero gradient. The wind velocity, or, respectively, the gradient, was then increased at 10 min intervals. Wind velocities up to 18·5 m/sec and gradients of 2, 4, 6 and 8 % were adopted. Treadmill speeds were 3·75 m/sec and 4·47 m/sec in running against wind, and 3·75, 4·03, 4·33 and 4·58 m/sec in running on gradients.

Walking against wind and walking on a gradient. These experiments were carried out according to the same plan as the running experiments. Seventeen experiments were performed. Treadmill speeds were 1·25 and 2·08 m/sec. The maximum wind velocity was 11·5 m/sec (22 knots) except in the experiment on J.B. at Farnborough in which the range of wind velocities was extended to 18·5 m/sec (37 knots).

Expired gas. 200–300 l. of expired gas were collected during the last 3–5 min of exercise at each wind velocity and gradient setting. The gas was passed through a recently calibrated gas meter. Gas samples were analysed in duplicate on a Lloyd gas analyser. Analyses were repeated and the apparatus checked, if differences between duplicates exceeded 0·03 % for CO_2 and 0·04 % for O_2.

RESULTS

Control observations. Values of $\dot{V}_{O_2}$ during 1 hr or more of walking and running at constant speeds are shown in Table 3. These results serve to illustrate the repeatability of the $\dot{V}_{O_2}$ determination and the consistency of the respiratory exchange ratio (r). Table 4 contains values of $\dot{V}_{O_2}$ per metre of distance traversed. It is seen that the $\dot{V}_{O_2}$/m in walking is less than it is in running, and the $\dot{V}_{O_2}$ in slow walking is less than in fast walking, as others have found (Margaria, Cerretelli, Aghemo & Sassi, 1963; Margaria, 1968*b*; Menier & Pugh, 1968).

TABLE 3. Time course of $\dot{V}_{O_2}$ and respiratory exchange ratio (r) for subject M.T. running at a constant speed of 4·5 m/sec and for subject J.B. walking at a constant speed of 1·25 m/sec

Time elapsed (min)	$\dot{V}_{O_2}$ (l./min)	r
M.T. (65 kg) running at 4·5 m/sec		
18	3·293	0·85
28	3·357	0·85
36	3·287	0·84
46	3·339	0·84
54	3·336	0·82
66	3·342	0·84
J.B. (75 kg) walking at 1·25 m/sec		
22	0·776	0·82
39	0·774	0·82
56	0·776	0·83
73	0·774	0·83
90	0·784	0·79

The within-subject variation in initial values of $\dot{V}_{O_2}$ at given treadmill speeds, on different days, ranged from 2 to 95 ml./min (mean 45 ml./min) for walking: for running the range was 273 ml./min. In the case of M. Turner running at 4·47 m/sec, $\dot{V}_{O_2}$ was 3·053 l./min in December, 1967, 3·127 l./min in September 1968, 3·235 l./min in May 1969, and 3·326 l./min in January 1970. Higher $\dot{V}_{O_2}$ was associated with fatigue after a race the previous day or reduced training following an injury.

Walking and running against wind. Fig. 3 shows the results of experiments on subjects walking and running at constant speeds against winds of up to 18·5 m/sec in velocity. In walking at 1·25 m/sec (4·5 km/hr) and running at 3·75 m/sec (13·5 km/hr) $\dot{V}_{O_2}$ was a linear function of v^2 up to the highest wind velocities (v). In running at 4·47 m/sec (16·1 km/hr) the relation was non-linear at wind velocities over 12·5 m/sec. This effect was associated with a change of running style imposed by the high work

TABLE 4. O_2 intake and energy cost per metre of distance traversed in walking and running at various speeds. In calculating net energy cost resting $\dot{V}_{O_2}$ was subtracted from the observed $\dot{V}_{O_2}$

Subject	Speed (m/sec)	Net O_2 intake (ml./kg m)	Net energy cost (cal/kg m)
		Walking	
J.B.	1·24	0·086	0·41
J.F.	1·23	0·093	0·45
R.H.	1·25	0·111	0·55
J.B.	1·75	0·117	0·57
J.F.	1·75	0·120	0·58
R.H.	—	—	—
J.B.	2·08	0·146	0·71
J.F.	2·11	0·132	0·67
R.H.	2·08	0·133	0·65
		Running	
M.T.	3·75	0·168	0·82
M.T.	4·47	0·174	0·85

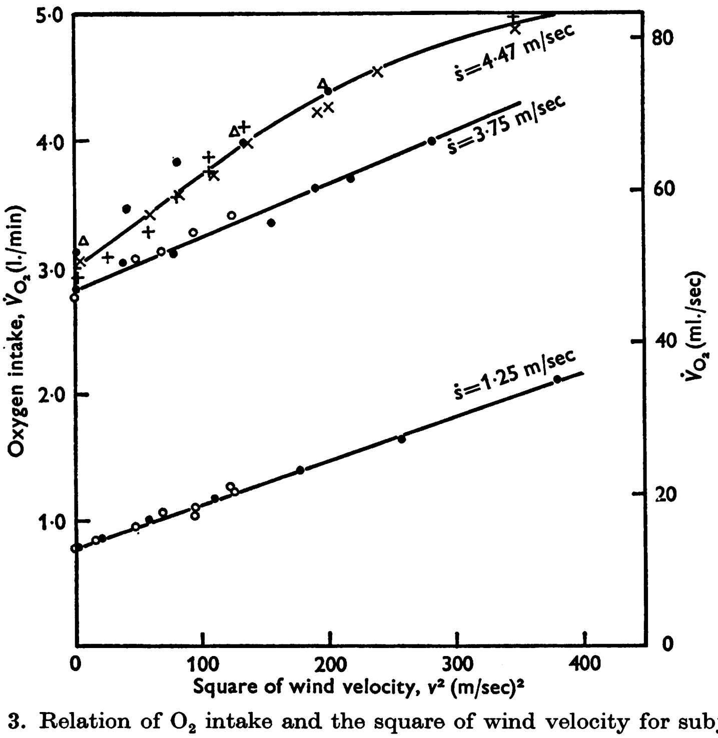


Fig. 3. Relation of O_2 intake and the square of wind velocity for subject M.T. running on the treadmill at 4·47 m/sec and 3·75 m/sec; and for subject J.B. walking on the treadmill at 1·25 m/sec. The regression equations were $y = 0{\cdot}0568x + 13{\cdot}22$ for $\dot{s} = 1{\cdot}25$ m/sec, $y = 0{\cdot}0678x \times 47{\cdot}27$ for $\dot{s} = 3{\cdot}75$ m/sec, and $y = 0{\cdot}1262x + 50{\cdot}17$ for $\dot{s} = 4{\cdot}47$ m/sec, with y in ml./sec and x in (m/sec)^2. Experiments ●, +, △ and × at Farnborough; ○ at Hampstead.

demand. The athlete had to increase his stride, run on his toes and lean further forward in order to maintain his forward velocity. There was some forward flexion of the trunk also at lower treadmill speeds but it was less marked. The slope of the graph of $\dot{V}_{O_2}$ against v^2 increased with increase of

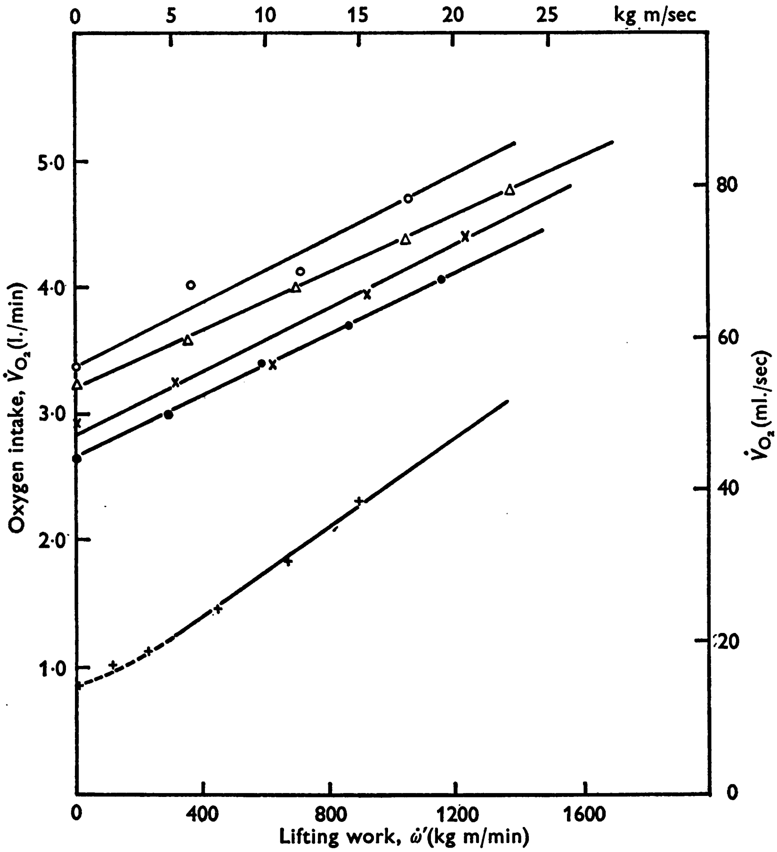


Fig. 4. Relation of O_2 intake and lifting work for subject M.T. running at constant speeds on increasing gradients, and for subject J.B. walking at a constant speed of 1·25 m/sec on increasing gradients. The mean of the regression equations for running on gradients was $y = 0{\cdot}0195x + 50{\cdot}81$. The regression equation for walking on gradients was $y = 0{\cdot}0292x + 11{\cdot}73$, with y in ml./sec and x in kg m/sec. J.B. walking at 1·25 m/sec +; M.T. running at 3·75 m/sec ●; M.T. running at 4·01 m/sec ×; M.T. running at 4·33 m/sec △; M.T. running at 4·58 m/sec ○.

treadmill speed in accordance with eqns. (6) and (8) which state that $\Delta\dot{V}_{O_2}$ is a function of $\dot{s}v$.

During running at 4·45 m/sec against a wind velocity of 18·5 m/sec $\dot{V}_{O_2}$ was 4·96 l./min compared with 3·05 l./min with minimal air movement. The extra O_2 intake ($\Delta\dot{V}_{O_2}$) in the presence of wind was, therefore, 1·91 l./min. $\dot{V}_{O_2}$ during walking at 1·25 m/sec increased from 0·79 l./min with minimal air movement to 2·10 l./min at a wind velocity of 18·5 m/sec. The extra O_2 intake ($\Delta\dot{V}_{O_2}$) was, therefore, 1·31 l./min.

Also shown in Fig. 3 are comparative results obtained at Farnborough and at Hampstead. On the whole the agreement was satisfactory, and although the Hampstead results have a slightly steeper slope than the corresponding Farnborough results, the differences are not larger than could be attributed to day-to-day variation in the air flow calibration.

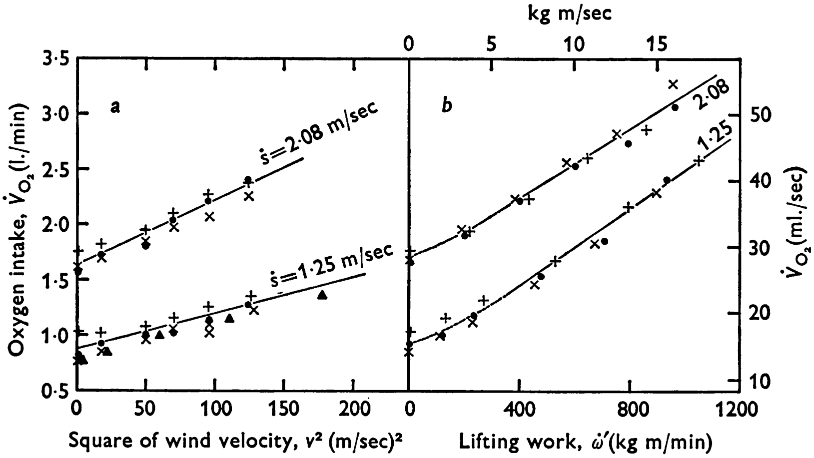


Fig. 5. Relation of O_2 intake and the square of wind velocity, and of O_2 intake and lifting work for subjects walking at constant speeds of 1·25 m/sec and 2·08 m/sec (*a*) at increasing wind velocities and zero gradient; and (*b*) on increasing gradients and with minimal air movement. The regression equations for $\dot{s}$ = 1·25 m/sec were $y = 0{\cdot}0523x + 14{\cdot}63$, and $y = 0{\cdot}0285x + 12{\cdot}75$ respectively for walking against wind and walking on gradients. The regression equations for $\dot{s}$ = 2·08 were $y = 0{\cdot}0953x + 27{\cdot}48$ for walking against wind, and $y = 0{\cdot}0260x + 26{\cdot}85$ for walking on gradients; y being in ml./sec and x in (m/sec)^2 for wind or kg m/sec for lifting work. Farnborough expt. J.B. ▲; Hampstead J.B. ×; Hampstead J.F. ●; Hampstead R.H. +.

Running on gradients. The results obtained on M.T. running on varying gradients are shown in Fig. 4. Lines have been calculated by the method of least squares. The plotted data were collected at long intervals, and the speeds and $\dot{V}'_{O_2}$ during the initial periods of horizontal running did not precisely match those used in the experiments on running against wind; however, the slopes of lines were strikingly uniform, showing that the O_2 cost of lifting work was essentially independent of running speed over the range of speeds investigated. This meant that the lifting work corresponding to a given wind velocity could be calculated from the average value of $\Delta\dot{V}'_{O_2}/\Delta\dot{\omega}'$ without significant error.

Walking against wind and walking on gradients. Fig. 5 illustrates the results obtained on the treadmill at Hampstead on three subjects walking against wind and walking on gradients. Each plotted value represents a single observation of $\dot{V}_{O_2}$. Regressions of $\dot{V}_{O_2}$ and v^2, and $\dot{V}'_{O_2}$ and $\dot{\omega}'$, were calculated for each subject and averaged. In the case of walking on gradients, values of $\dot{V}'_{O_2}$ for $\dot{\omega}' < 300$ kg m/min were not used in calculating the regressions as the relation was clearly non-linear in this range. The result for one subject (R.H.) was non-linear for walking against wind, as well as for walking on gradients. This did not, however, affect the mean regression significantly.

Force exerted against wind in terms of the equivalent force exerted against gravity. Values of $\dot{\omega}'$ and v^2 for walking at equal O_2 intakes and treadmill speeds were read off the graph shown in Fig. 5. Similar values for running were calculated from the results in Fig. 3 and the mean regression of $\dot{V}'_{O_2}$ and $\dot{\omega}'$ from Fig. 4. Plotting $\dot{\omega}'$ against v^2, we obtain

$$\dot{\omega}' = Kv^2$$

and substituting from eqn. (11)

$$F = \frac{Kv^2}{\dot{s}}.$$

Dividing through by the mean projected area A_p and writing F' for F/A_p we get

$$F' = \frac{Kv^2}{\dot{s}A_p}, \tag{17}$$

where F' is the vertical force in kg/m² equivalent to the horizontal force per square metre of projected area at wind of velocity v. This relation is shown in Fig. 6. It is seen that the relation is slightly non-linear at low v^2 in the case of walking, and at high v^2 in the case of running at 4·47 m/sec. This is explained by corresponding deviations from linearity in the $\dot{V}_{O_2}/v^2$ and $\dot{V}'_{O_2}/\dot{\omega}'$ graphs. The graph of F and v^2 for slow running is linear, although the slope is smaller than the other slopes, which agree closely.

Direct evaluation of drag from wind pressure on plane and rounded surfaces. The graphs of wind pressure and wind velocity for plane surfaces and for the elliptical cylinder are shown in Fig. 7. It is seen that the plane surface matching the outline of subject J.B. had the same drag coefficient as the rectangle of similar area. The result for the rectangle was similar to published data in the engineering literature, as was the result obtained with the elliptical cylinder. The drag coefficient of the latter which was 1·04 was comparable with that of Hill's (1927) model of a runner. Also shown for comparison is the average line for the equivalent vertical force (F') calculated from the results in Fig. 6. This has a considerably smaller slope.

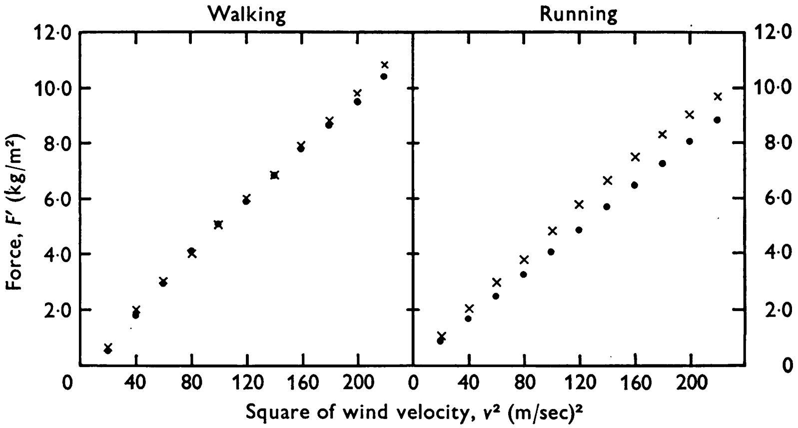


Fig. 6. The equivalent vertical force (F') at varying wind velocities plotted against the square of wind velocity. The equivalent vertical force was calculated by comparison of $\dot{V}_{O_2}$ in work against wind and work on a gradient. Results are shown for two walking speeds (● 1·25 m/sec, × 2·08 m/sec) and two running speeds (● 3·75 m/sec, × 4·47 m/sec). For the derivation of F' see eqn. (19).

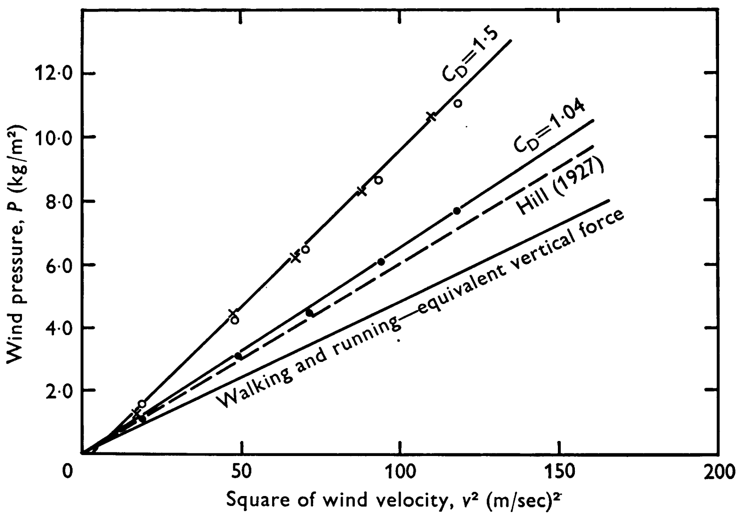


Fig. 7. The relation of wind pressure and the square of wind velocity, measured on objects having the same projected area as subject J.B. (○ man-shaped board, × rectangle, ● elliptical cylinder). Also shown is the relation obtained by Hill (1927) with an 8 in. high model in a wind-tunnel, and the physiological relation (equivalent vertical force) obtained by comparison of O_2 intakes during work against wind with O_2 intakes during work on gradients.

Apparent efficiency of work against wind and work against gravity. Table 5 contains (*a*) values for the apparent efficiency of the equivalent vertical work ($\dot{\omega}'$) corresponding to two wind velocities, and (*b*) values of apparent efficiency of work against wind calculated from observed $\dot{V}_{O_2}$ and wind

TABLE 5. Apparent efficiency at two values of v^2 (*a*) of equivalent vertical work ($\dot{\omega}'$) calculated from v^2 and $\dot{\omega}'$ at equal $\dot{V}_{O_2}$, and (*b*) of horizontal work estimated from $\dot{V}_{O_2}$ and direct measurements of wind pressure (P). $\dot{s}$ = treadmill speed, v = wind velocity, F' = equivalent vertical force, P = observed wind pressure at wind velocity v; apparent efficiency (e) = $F\dot{s}/2{\cdot}09\Delta\dot{V}_{O_2}$. The results show that horizontal work against wind is more efficient than the corresponding vertical work on a gradient

A. Equivalent vertical work on gradient

$\dot{s}$ (m/sec)	v^2 (m/sec)^2	F/A_p (kg/m^2)	F (kg)	$\Delta\dot{V}_{O_2}$ (ml./sec)	$F\dot{s}$ (kg m/sec)	Apparent efficiency
			Walking			
1·25	100	5·1	3·22	5·5	4·03	0·351
2·08	100	5·1	3·22	9·7	6·70	0·331
1·25	200	9·5	5·99	10·8	7·49	0·332
2·08	200	9·85	6·21	19·3	12·92	0·320
						Mean 0·334
			Running			
3·75	100	40·5	1·94	6·8	7·28	0·512
4·47	100	4·85	2·32	12·6	10·37	0·394
3·75	200	8·05	3·85	13·6	14·44	0·508
4·47	200	9·1	4·35	22·7	19·44	0·410
						Mean 0·456

B. Work against wind

$\dot{s}$ (m/sec)	v^2 (m/sec)^2	P/A_p (kg/m^2)	P (kg)	$\Delta\dot{V}_{O_2}$ (ml./sec)	$P\dot{s}$ (kg m/sec)	Apparent efficiency
			Walking			
1·25	100	6·5	4·10	5·5	5·13	0·446
2·08	100	6·5	4·10	9·7	8·53	0·421
1·25	200	13·05	8·23	10·8	10·29	0·456
2·08	200	13·05	8·23	19·3	17·12	0·424
						Mean 0·437
			Running			
3·75	100	6·5	3·11	6·8	11·66	0·820
4·47	100	6·5	3·11	12·6	13·90	0·528
3·75	200	13·05	6·24	13·6	23·40	0·823
4·47	200	13·05	6·24	22·7	27·89	0·588
						Mean 0·690

pressure P. In spite of the major increase in O_2 cost per metre with increase of speed in walking, the apparent efficiency of lifting work was independent of walking speed. Somewhat higher efficiency values were obtained for the equivalent vertical work in running, and in running the efficiency was higher at the slower speed, in spite of the fact that the O_2 cost per metre in horizontal running is independent of speed. The extremely high efficiency value for running at 3·75 m/sec requires confirmation.

These results show that the apparent efficiency of work against wind is greater than the apparent efficiency of the corresponding work against gravity, as in walking or running on a gradient.

Additional results

Effect of shielding. Fig. 8 contains results obtained at varying air velocities with 2 runners on the treadmill. The subject M.T. ran about 1 m behind his companion. The treadmill speed was 4·5 m/sec. After the first

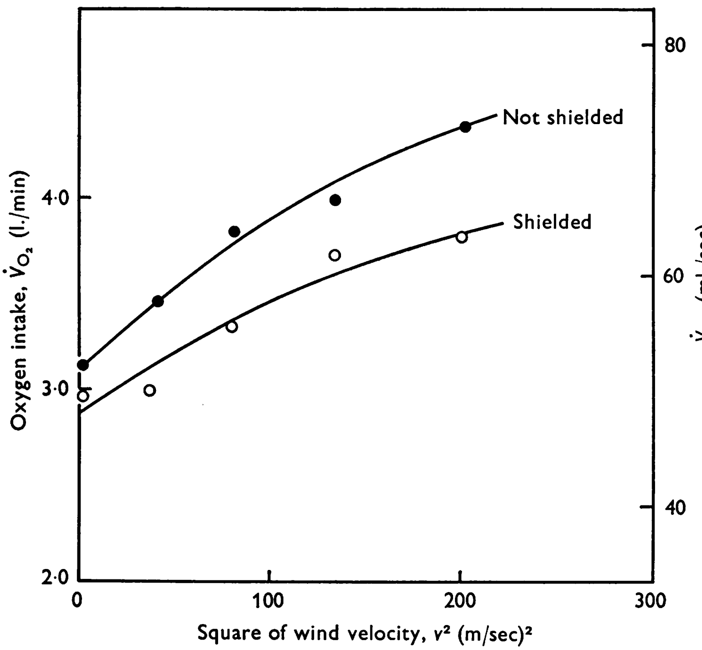


Fig. 8. O_2 intake and the square of wind velocity for subject M.T. running at 4·46 m/sec against varying wind velocities (*a*) alone on the treadmill and (*b*) behind another runner.

session the observations were repeated with M.T. running alone on the treadmill. Fig. 8 shows the reduction in $\dot{V}_{O_2}$ achieved by running behind another runner. The difference was 0·250 l./min at a wind velocity of 6·0 m/sec which is representative of the speed of running in a 5000 m or 1000 m race. Since $\Delta \dot{V}_{O_2} \propto \dot{s}v^2$, the extra $\dot{V}_{O_2}$ of 0·250 l./min at $\dot{s}$ = 4·5 m/sec becomes $0{\cdot}250 \times 6{\cdot}0/4{\cdot}5 = 0{\cdot}332$ l./min for $\dot{s}$ = 6·0 m/sec. On the running track in calm air $\dot{s}$ and v are, of course, equal. When running at this speed, M.T. reaches his maximum $\dot{V}_{O_2}$ of 5·0 l./min and in the absence of air resistance his $\dot{V}_{O_2}$ should be $0·332/5·0 \times 100 = 8\%$ less or 4·6 l./min. By running close behind another runner, therefore, $\dot{V}_{O_2}$ should be reduced to $5·0 - 0·332 = 4·668$ l./min, which is 6·5 % less than the $\dot{V}_{O_2}$ without shielding. Thus 80 % of the energy cost of overcoming air resistance can

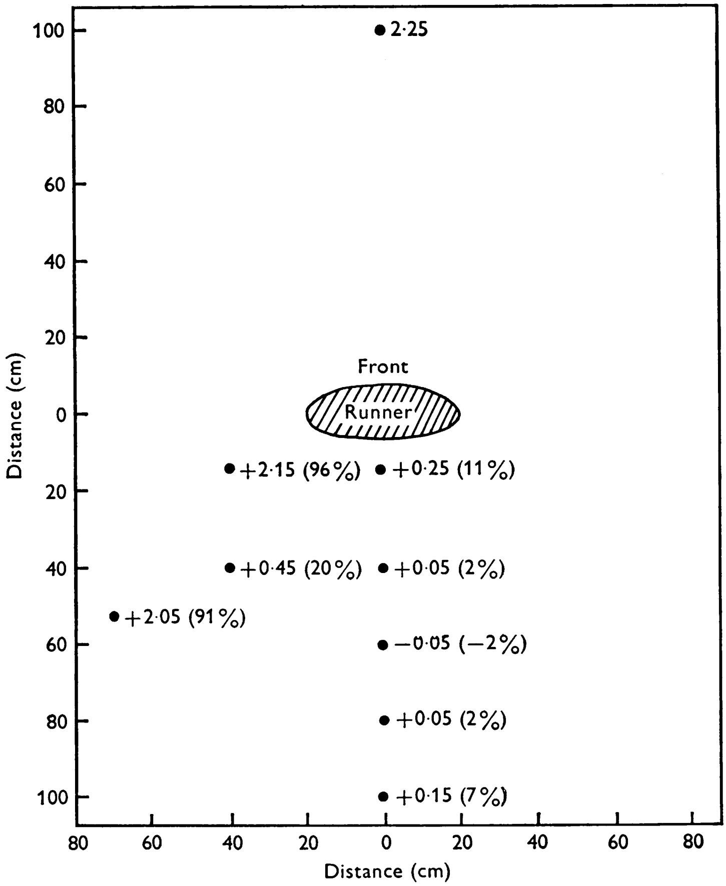


Fig. 9. Plan of the dynamic air pressure in kg/m² at various distances from a runner in the presence of a wind of 6 m/sec as in middle distance racing. The numbers are air pressures measured with the Pitotstatic tube. The values in parentheses give the percentage pressure compared with the pressure ahead of the runner.

be abolished by shielding. Confirmation of this result was obtained by measurements of dynamic air pressure with a Pitotstatic tube. The apparatus was set up in various positions, to the side of, behind, and ahead of a subject standing on the treadmill, and at a height of 125 cm. With an air flow of 6 m/sec the dynamic pressure ahead of the subject was 2·25 kg/m^2; one metre behind the subject the pressure was 0·15 kg/m^2. The pressure was also considerably reduced behind and to one side of the subject (Fig. 9).

DISCUSSION

Wind tunnel turbulence. Measurements of drag performed in different wind tunnels may show considerable variation owing to the effect of turbulent fluctuations of the air stream. This was one reason for making direct measurements of the pressure/velocity relation using plane and rounded surfaces of the same projected area as one of the subjects. The finding that the drag coefficients obtained with these bodies agreed well with published data was regarded as evidence that the air-flow calibration was satisfactory.

It is known that the drag coefficients of moving bodies in free air is similar to the values observed in low-turbulence wind tunnels, and that turbulent eddies in the free atmosphere do not affect drag significantly owing to their large amplitude and low velocity (Millikan & Klein, 1933). Turbulence of the air stream in a wind tunnel, on the other hand, may be expected to affect C_D in two ways (Hoerner, 1965*c*, *d*): (1) there may be a 5–10 % increase in drag at subcritical Reynold's numbers (i.e. in the range considered in this investigation) and (2), there may be a reduction of the critical Reynold's number with consequent lowering of the apparent drag at high wind velocity.

Reynold's number. Fig. 1 shows that for a cylinder of the average width of a man, the Reynold's number at the upper end of the wind velocity range employed in these experiments approaches R_{crit}. The question, therefore, arises whether the change in the slope of $\dot{V}_{O_2}$ against v^2 in running at 4·5 m/min can be attributed to a change in C_D due to variation in R. There are many factors affecting R_{crit} such as roughness or irregularities of surface, variations in limb and trunk dimensions, wind turbulence etc., and it is impossible at present to estimate R_{crit} for man, particularly for man during movement. The fact that the $\dot{V}_{O_2}/v^2$ relation was linear at lower treadmill speeds is, however, strong evidence that the levelling of $\dot{V}_{O_2}$ at high v^2 during running was not due to variation in Reynold's number. The change in style described by the athlete may be relevant, since excessive forward inclination of the trunk would result in part of the drag being converted to lift. The effect is unlikely to have been due to O_2 debt, as it began at submaximal O_2 intakes; nor is experimental error likely since the observations were confirmed on four occasions.

Comparison with previous results. Pugh (1970) compared O_2 intakes in athletes running on the track and the treadmill. The difference between $\dot{V}_{O_2}$ on the treadmill (which eliminates air resistance) and $\dot{V}_{O_2}$ on the track was about 8 % at the middle distance speed of 6 m/sec. A similar value was obtained from results collected on M. Turner running against wind. The relation of $\Delta \dot{V}_{O_2}$ and v^2 for $\dot{s}$ = 4·42 m/sec derived from those results was as follows.

$$\Delta \dot{V}_{O_2} = 0{\cdot}00891 v^2$$

with $\dot{V}_{O_2}$ in l./min and v in m/sec. The present findings yielded

$$\Delta \dot{V}_{O_2} = 0{\cdot}00757 v^2$$

for a treadmill speed of 4·47 m/sec. (18)

The agreement is as good as can be expected in view of the difficulties involved in air-flow measurements.

For running at a slower speed (3·75 m/sec)

$$\Delta \dot{V}_{O_2} = 0{\cdot}00407 v^2. \tag{19}$$

After correcting to a speed of 4·47 m/sec the coefficient of v^2 is

$$0{\cdot}00407 \times 4{\cdot}47/3{\cdot}75 = 0{\cdot}00485.$$

The Hampstead result for running against wind at 3·75 m/sec yielded a slope of 0·00508 which for $\dot{s}$ = 4·47 would be 0·00606. Although these differences may seem rather large they correspond with a variation in air flow of only 1 m/sec at a wind velocity of 10 m/sec. Accordingly the question whether running speed influences the drag coefficient must be left open.

In the case of walking, the relation of $\dot{V}_{O_2}$ and v^2 on the treadmill is linear for work against wind, but not for work on a gradient. This observation suggests differences in the mechanics of work against horizontal and vertical forces.

Mechanical efficiency. The calculation of efficiency as $\dot{\omega}/2{\cdot}09\Delta \dot{V}_{O_2}$ is similar in principle to the accepted practice of calculating efficiency from $\dot{\omega}(\dot{V}_{O_2} - \dot{V}_{O_2}$ resting), the only difference being that the $\dot{V}_{O_2}$ at speed $\dot{s}$ and zero gradient is used instead of resting $\dot{V}_{O_2}$. This method yields information on the increase in energy expenditure to be expected when a person encounters wind or climbs a hill. It does not tell us anything about the mechanical efficiency of contracting muscle or how the extra work is distributed within each stride.

Margaria (1968*b*) has claimed that the efficiency of vertical work is similar to that of contracting muscle, i.e. about 0·25 and similar to the efficiency of other slow forms of exercise where elastic and inertial forces do not have to be considered. He calculated efficiency from the relation $\dot{\omega}/(E - \text{basal } E)$. This method, of course, gives very low values of e at small gradients where the lifting work accounts for but a small fraction of the observed $\dot{V}_{O_2}$. However, e increases with increase of gradient and becomes constant at about 0·25 at slopes of 30 % and over, when inertial and elastic forces are small. This approach is relevant to the biomechanics of exercise but is of less value from a practical point of view than the empirical definition of e used here.

There seems to be no doubt that the apparent efficiency of work against a horizontal force in the form of wind is greater than the apparent efficiency of work against the vertical force of gravity. This probably means that there are differences in the way in which the extra work is distributed between the phase of positive work at the beginning of a stride and the phase of negative work towards the end of it (Margaria, 1968*b*).

According to Margaria (1968*b*) the positive work done in walking up-hill is accompanied by a diminution of the negative work. Consequently the total work which is the algebraic sum of positive and negative work is less than that calculated from the rate of ascent; also the efficiency is greater on a steep slope when there is no negative component. Clearly the distribution of horizontal work against wind is likely to be somewhat different and requires further consideration. If we accept Margaria's definition of efficiency and take the efficiency of work against air resistance as being similar to that of contracting muscle, then the energy cost of athletic events cannot, as he pointed out (Margaria, 1968*a*), be calculated by adding together terms for the energy cost of work against air resistance, acceleration and horizontal progression as Lloyd (1967) has done in his mathematical analysis of athletic events. On the other hand, if one uses the apparent efficiency as defined in eqns. (9) and (14) instead of Margaria's (1968*b*) value, no such discrepancy arises. Thus, if we wish to estimate the energy cost of an activity from the sum of its components, the apparent efficiency and not the efficiency as defined by Margaria (1968*b*) must be used. Nor can the energy cost of work against wind be validly calculated in terms of the observed energy cost of running on an equivalent gradient, since e and e' are not equal (eqn. (17)).

Practical implications. The $\dot{V}_{O_2}$ determination provides a means of comparing the relative energy cost of different forms of work. The results collected on M. Turner show that running at marathon speed (4·5 m/sec) against a strong wind (37 knots) is equivalent to 1770 kg m/min of lifting work on a gradient or climbing a hill at the formidable rate of 1609 m in 1 hr. A $\dot{V}_{O_2}$ of 5·0 l./min in running was equivalent to 2700 kg m/min on the bicycle ergometer, and the corresponding $\Delta\dot{V}_{O_2}$ of 2·0 l./min was equivalent to a work rate of 1050 kg m/min on the ergometer. In practice M.T. cannot sustain a $\dot{V}_{O_2}$ of 5·0 l./min in ergometer exercise, his maximum being 4·6 l./min for that kind of exercise (Pugh, 1967).

$\Delta\dot{V}_{O_2}$ in walking against wind was considerably less than in running against wind, the reason being that $\dot{V}_{O_2}$ varies as $\dot{s}v^2$ where $\dot{s}$ is the speed of progression and v is the wind velocity. In terms of unit body weight and at a wind velocity of 18·5 m/sec the $\Delta\dot{V}_{O_2}$ for walking at 1·25 m/sec (4·5 km/hr) was 17·5 ml./kg min compared with 34 ml./kg min for running at 4·5 m/sec (16·2 km/hr). At the higher walking speed of 2·1 m/sec (7·2 km/hr) $\dot{V}_{O_2}$ may be expected to increase from 1·5 to 3·6 l./min, which is the maximum $\dot{V}_{O_2}$ of most hill-walkers (L. G. C. E. Pugh, unpublished results). At the slower speed of 1·25 m/sec, $\dot{V}_{O_2}$ increased from 0·77 to 2·1 l./min or about 55 % of the average subject's capacity. In view of these findings it is easy to understand why some hikers become exhausted in bad weather and fail to complete routes that would be well within their capacity in good conditions. Another practical point that arises from the $\dot{V}_{O_2}/\dot{s}v^2$ relation is that the energy expended in walking against gale force winds is much reduced by walking slowly; however, the rate of progress, of course, will be correspondingly slower and may render it impossible for a party to reach shelter before night-fall.

With regard to running the present results yield $\Delta\dot{V}_{O_2} = 0{\cdot}00354\ A_p v^3$ for running on a track in calm air, $\Delta\dot{V}_{O_2}$ being in l./min and v in m/sec (see Pugh, 1970). It was shown previously that A_p is approximately equal to the du Bois surface area in $m^2 \times 0{\cdot}266$. For running at middle distance speeds (6·0 m/sec) the energy cost of overcoming air resistance (calculated as $\Delta\dot{V}_{O_2}$) works out at 7·5 % of the total energy cost and for sprinting (100 m in 10 sec) the corresponding estimate is 13·6 %. The previous estimates were 8 and 16 % respectively (Pugh, 1970).

It was found that at a speed of 6 m/sec, 80 % of the O_2 cost of meeting air resistance was eliminated by running close behind another runner. Unless some other adverse effect is present to cancel this advantage, an athlete should be able to exceed the speed corresponding to his $\dot{V}_{O_2 max}$ by up to $7{\cdot}5 \times 0{\cdot}80 = 6$ %, by running behind a pace-maker or a faster competitor. According to the relation of $\dot{V}_{O_2}$ and speed in track running found by Pugh (1970), the $\dot{V}_{O_2}$ corresponding to a speed of 6 m/sec is 76 ml./kg min and the speed corresponding to a 6 % greater $\dot{V}_{O_2}$ (i.e. a $\dot{V}_{O_2}$ of 80·5 ml./kg min) is 6·4 m/sec. This is equivalent to a reduction in time for a 400 m lap from 66·6 to 62·5 sec. Track experience, however, suggests that athletes cannot run close enough to gain as much advantage as this. Running behind and to one side in the position shown in Fig. 9, the gain might be 1 sec per lap which is more in line with experience. The effect of shielding is, of course, well known to athletes and team managers, but they have regarded it as a subjective effect. The observation that it has a physiological basis may enable them to use it with greater tactical understanding than before.

Grateful acknowledgement is made to the subjects of these experiments, to Mr A. Crisp and Miss Sandra Alder for their technical assistance as well as to Miss P. Woodward for statistical advice. Dr J. Brotherhood, as well as acting as a subject, also assisted in conducting experiments. I am also indebted to the Institute of Aviation Medicine, Farnborough, for the use of their Climatic Chamber and to Mr R. P. Clark and Mr G. J. Hughes for aerodynamical advice.

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