Effects of wind assistance and resistance on the forward motion of a runner

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DAVIES, C. T. M. *Effects of wind assistance and resistance on the forward motion of a runner.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 48(4): 702–709, 1980.—The aerobic energy cost ($\Delta \dot{V}_{O_2}$) of running at different speeds (V) with and against a range of wind velocities (W_V) has been studied in a wind tunnel on three healthy male subjects and the results compared with downhill and uphill gradient running on a motor-driven treadmill. In terms of equivalent horizontal and vertical forces, comparison showed that the two forms of exercise were physiologically identical for gradients and W_V ranging from -10 to $+5\%$ and 1.5 to 15 $m \cdot s^{-1}$, respectively. The apparent mechanical efficiencies of the work performed with a head and following wind were approximately $+0.35$ and -1.2. At $W_V >$ 15 $m \cdot s^{-1}$ it was more efficient to run against the wind and the corresponding gradient on the treadmill. At high W_V the subjects altered their posture and "leaned" into the wind, thus possibly converting potential drag into body lift. The energy cost of overcoming air resistance on a calm day outdoor was calculated to be 7.8% for sprinting (10 $m \cdot s^{-1}$), 4% middle-distance (6 $m \cdot s^{-1}$), and 2% marathon (5 $m \cdot s^{-1}$) running.

oxygen intake; aerobic exercise; gradient; treadmill; positive and negative work

THE AEROBIC ENERGY COST of level and gradient exercise has been studied many times (see Ref. 12), but the influence of wind resistance on oxygen intake ($\dot{V}_{O_2}$) has received comparatively little attention. Margaria (9) discusses the problem on the basis of Fenn's early observations (6, 7) and Hill's (8) work with a model of a runner in a wind tunnel, in which it was suggested that there might be an exact equivalence between working against horizontal forces produced by different air velocities (W_V) outdoor and the vertical forces involved in gradient exercise on a conventional (indoor) laboratory treadmill where air resistance is effectively eliminated, but only Pugh (13, 14), to the author's knowledge, has made observations of this type. Pugh (13, 14) found in four subjects exercising on a treadmill housed inside a wind tunnel that the energy cost of a head wind was proportional to W_V^2, but the effect was dependent on the runners' speed (V), and no precise equivalence between gradient and level "wind-resistance" running could be seen. The horizontal work against the wind was always performed more efficiently than the vertical work against gravity. Further, Pugh (14) calculated that the energy cost of overcoming air resistance outdoors and suggested, even at middle-distance speeds, that it might account for

at least 8% of the total $\dot{V}_{O_2}$, a value four times in excess of Hill's (8) original prediction. It is therefore of interest that recently McKiken and Daniels (11) have failed to show any differences between measured $\dot{V}_{O_2}$ for outdoor track and indoor treadmill running over a range of long- and middle-distance speeds. Further no one to the author's knowledge has considered or attempted to measure the effects of a following wind on the forward motion of a runner.

To gain further information on the effects of a head and following wind on the forward motion of a runner, the present investigation was planned in three parts. *1*) Experiments were conducted on three healthy male subjects who ran on a motor-driven treadmill with and against wind velocities equivalent to their running speed; this type of running is often encountered outdoor. *2*) The experiments were extended to very high (gale-force) head and following winds similar in intensity to those experienced by climbers. *3*) Comparison of the work with and against the horizontal forces encountered in *1* and *2* were made with the vertical work of running with and against gravity during downhill and uphill gradient exercise, respectively, on the same subjects.

MATERIALS AND METHODS

The physical characteristics of the three healthy male subjects studied are given in Table 1. *Subjects 1* and *2* were endurance athletes in regular training (100–150 miles/wk) and *subject 3* was active and ran regularly for pleasure. Measurements were normally made after a light meal. The experiments were conducted over a 12-mo period at two laboratories. The level and gradient running experiments were carried out at the author's laboratory and the wind resistance studied at the Institute of Aviation Medicine, Farnborough. In the level and gradient running experiments, the subjects ran continuously at set speeds and the slope of the treadmill bed was raised every 10 min by approximately 2% increments. Both negative (downhill) and positive (uphill) gradients were investigated at zero wind resistance and $\dot{V}_{O_2}$ levels were measured during the final 4 min at each load using the standard (Douglas bag) open-circuit technique. Duplicate (and more often triplicate) Douglas bag samples were taken at each load and the data presented are the mean $\dot{V}_{O_2}$ values for each collection period. The experiments running with and against a wind were made in a

TABLE 1. *Physical characteristics of subjects*

Subj No.	Wt, kg	Ht, cm	A_D, m^2	$\dot{V}_{O_2\,max}$, l·min^{-1}
1	65	173	1.78	4.72
2	66	185	1.88	5.01
3	62	178	1.78	3.90

A_D, DuBois surface area; $\dot{V}_{O_2\,max}$, maximal aerobic power output.

climatic chamber where the airstream produced by a high-power (propeller) fan was deflected through an angle of 90° by a set of vertical vanes 3 m in front of the treadmill. Wind velocities of 1.5–18.5 m·s^{-1} (40 mph) were available. The airflow was turbulent particularly at high velocities; vane anemometer readings fluctuated by 1 m·s^{-1} across the chamber at the highest fan setting. The subjects again ran continuously and the same protocol (including the methods for measuring $\dot{V}_{O_2}$) as described for gradient running was used. The fan setting (and therefore airflow) was increased every 10 min and the subject maintained a constant pace on the treadmill at zero grade. Usually five fan settings and two running (treadmill belt) speeds were studied (on different days) and the experiments were repeated with the mill of the treadmill reversed. The same fan settings were used for each set of experiments and air velocity was checked several times at each setting at representative points at the head of the treadmill. The projected area of the subjects running with and against the wind was estimated from photographs taken during the experiments beside a rectangular surface of known area following the method of Pugh (13).

Calculations from the raw data were made on the following basis. Air resistance or drag (D) is proportion to αW_V^2, where W_V is the wind velocity and α is the proportionality constant for a given object. The relationship between D and W_V is normally expressed in terms of the drag coefficient (C_D); thus $C_D = D/\beta A_r$, where β is the dynamic pressure and is equal to $0.5\,\rho W_V^2$ and A_r is the projected area of the runner. ρ is the air density. Thus, if D is expressed in kilogram force and A_r in square meters, then

$$C_D = \frac{\alpha}{0.5\rho\ A_r} = \frac{\alpha}{0.0625\ A_r} \qquad (1)$$

In this study α was obtained by constructing graphs relating $\dot{V}_{O_2}$ to W_V^2 and $\dot{V}_{O_2}$ to (lifting) work rate ($\dot{W}$) on the treadmill. Values of W_V^2 and $\dot{W}$ at equal $\dot{V}_{O_2}$ were read off and $\dot{W}$ was divided by V to obtain the total force (F) opposing motion. α was calculated at the slope of the F/W_V^2 line. The confounding influence of a change in Reynolds' number (R) on D was avoided in the present experiments by confining the W_V range from 1.5 to 18 m·s^{-1}. From laboratory experiments on cylindrical models similar in overall dimensions to man, the effects of R on C_D are relatively constant: critical Reynolds' numbers are only reached at W_V in excess of 18.5 m·s^{-1}. The interested reader is referred to Pugh (14) for a more detailed treatment and analysis of the problem of calculating D and the influence of R during treadmill running in a wind tunnel.
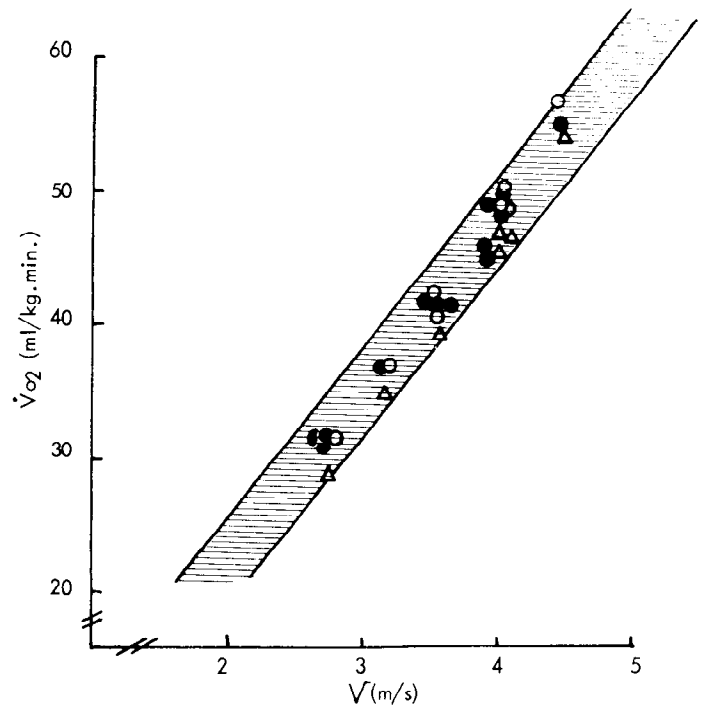

FIG. 1. Oxygen intake ($\dot{V}_{O_2}$) running with ($\triangle$) and against ($\bigcirc$) a given wind velocity equivalent to speed of Farnborough treadmill. Unit treadmill ($\bullet$) at minimal air velocity (see METHODS). *Hatched area* represents intrasubject variation (95% confidence limits) of $\dot{V}_{O_2}$ against a speed for subject measured on 33 separate occasions on Unit treadmill. Comparison of two treadmills used in this investigation at minimal airflows for each subject over a range of speeds yielded no statistically significant differences.

RESULTS

The effects on $\dot{V}_{O_2}$ of running with and against a wind at a velocity equivalent to the speed of the treadmill (i.e., below 5 m·s^{-1}) were marginal and certainly within the intrasubject variation of $\dot{V}_{O_2}$ for running at minimal W_V on the two treadmills used in this investigation (Fig. 1). However, as W_V increased the cost of work, the $\dot{V}_{O_2}$ rose as a curvilinear function of W_V (Fig. 2). At high air velocities (>15 m·s^{-1}) $\dot{V}_{O_2}$ tended to plateau and approach an asymptotic value. The effect of increasing the treadmill speed (V) was a parallel displacement of the $\dot{V}_{O_2}/W_V$ curve to the left. Thus, the effects of V could be removed by plotting the change in oxygen intake ($\Delta\dot{V}_{O_2}$) from a base line of minimal W_V for each exercise intensity. Running with the wind effected a curvilinear reduction in $\dot{V}_{O_2}$, but the changes were less marked than for exercise against a head wind. Changes in V produced an upward displacement in the $\dot{V}_{O_2}/W_V$ curve.

The curvilinear nature of the $\dot{V}_{O_2}/W_V$ curve (but not the plateau effect) could be removed by considering $\Delta\dot{V}_{O_2}$ (ml·kg^{-1}·min^{-1}) as a function of W_V^2 at the different levels of V used in this study. The relationship between the two variables for running with and against the wind are shown in Fig. 3. $\Delta\dot{V}_{O_2}$ is essentially a linear function of W_V^2 over the range of W_V from 5 to 15 m·s^{-1}; at the higher W_V the increase in $\Delta\dot{V}_{O_2}$ diminishes and $\Delta\dot{V}_{O_2}/W_V^2$ relationship levels off. The association of $\Delta\dot{V}_{O_2}$ with W_V^2 is independent of V and if $\Delta\dot{V}_{O_2}$ is expressed in milliliters per kilogram (body wt) per minute and W_V^2 in
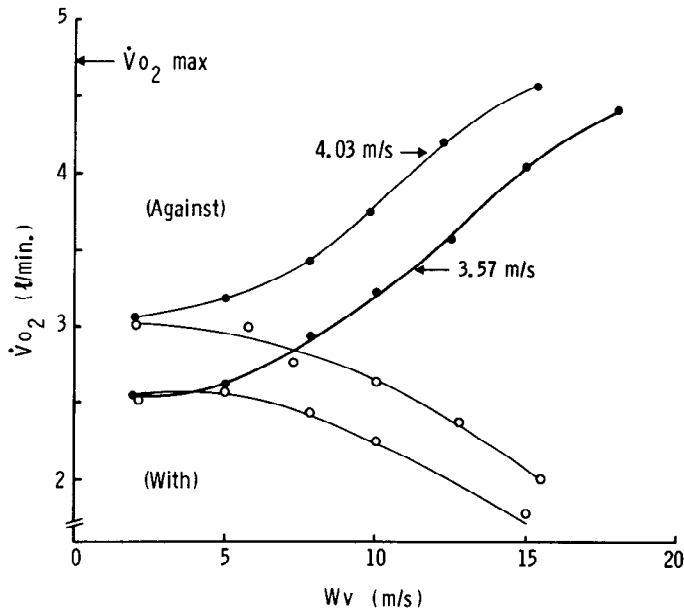
FIG. 2. Typical relationship of $\dot{V}o_2$ to wind velocity (W_V) over range studied in this investigation (*subj 1*). Data points are shown for two treadmill speeds (3.57 and 4.03 $m \cdot s^{-1}$), with (○) and against (●) the wind. *Arrow* marks $\dot{V}o_{2\,max}$ of subject.

meters per second the relationship between the two variables for exercise against and with the wind can be described by the following equations

$\dot{V}o_2$ $(ml \cdot kg^{-1} \cdot min^{-1})$

$= -0.700 + 0.109\ W_V^2$ $(m \cdot s^{-1})$ (against); $r = +0.993$

and

$\dot{V}o_2$ $(ml \cdot kg^{-1} \cdot min^{-1})$

$= -0.054 - 0.655\ W_V^2$ $(m \cdot s^{-1})$ (with); $r = -0.954$

Because the force (F) of the wind has been found to be proportional to W_V^2 (see METHODS), one should expect the work per unit time (F × V) of running against the wind to vary as the cube of its velocity. In Fig. 4 the power output ($\dot{W}$) required (expressed as $kg \cdot m \cdot kg^{-1} \cdot s^{-1}$) to overtake air resistance is plotted against W_V^3 together with the original data of Hill (8). The results from the present and Hill's earlier experiments are in close agreement over the range of W_V up to approximately 12 $m \cdot s^{-1}$. The slope of the curve over this range is given by

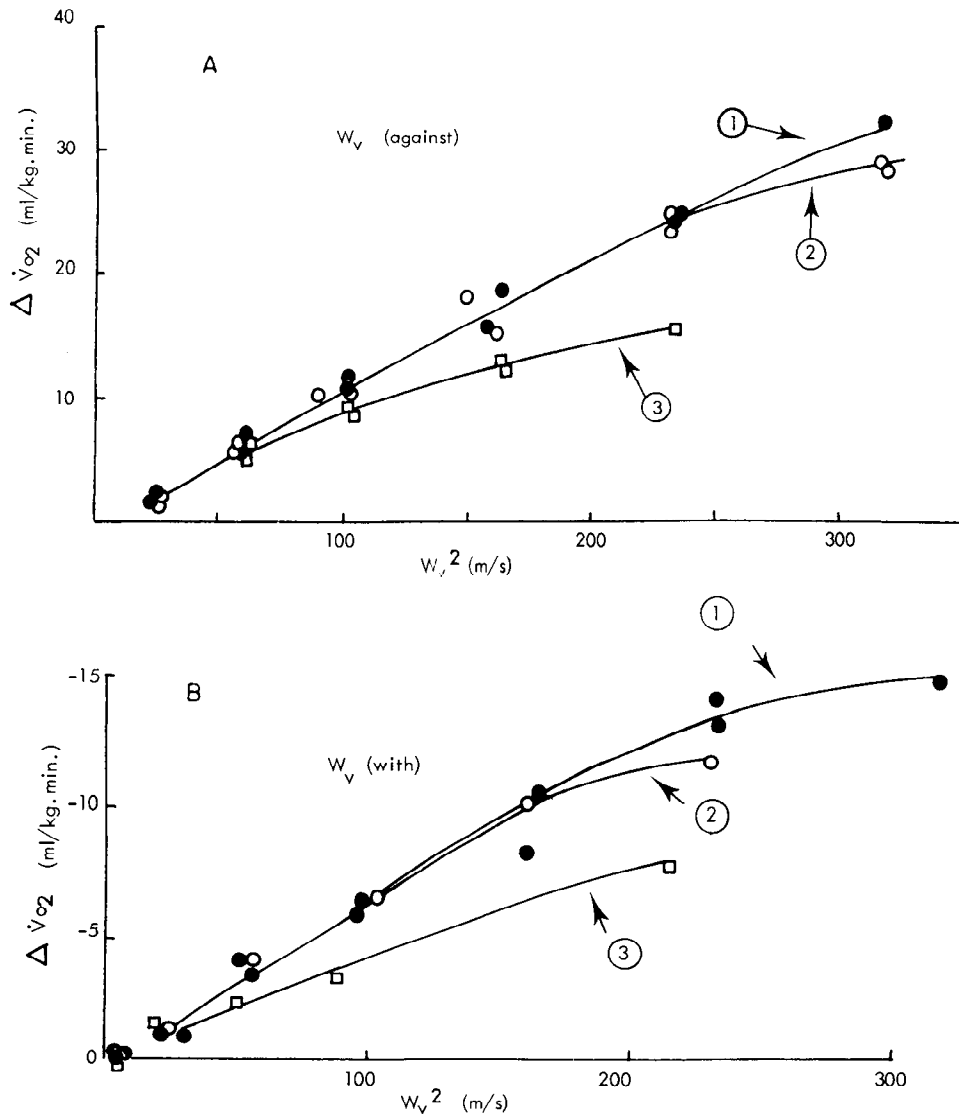$\dot{W}$ $(kg \cdot m \cdot kg^{-1} \cdot s^{-1}) = 0.00034\ W_V^3$ $(m \cdot s^{-1})$

FIG. 3. Change in oxygen intake ($\Delta \dot{V}o_2$) in relation to W_V^2 for *subj 1* (●), *subj 2* (○), and *subj 3* (□) against (*A*) and with (*B*) the wind.
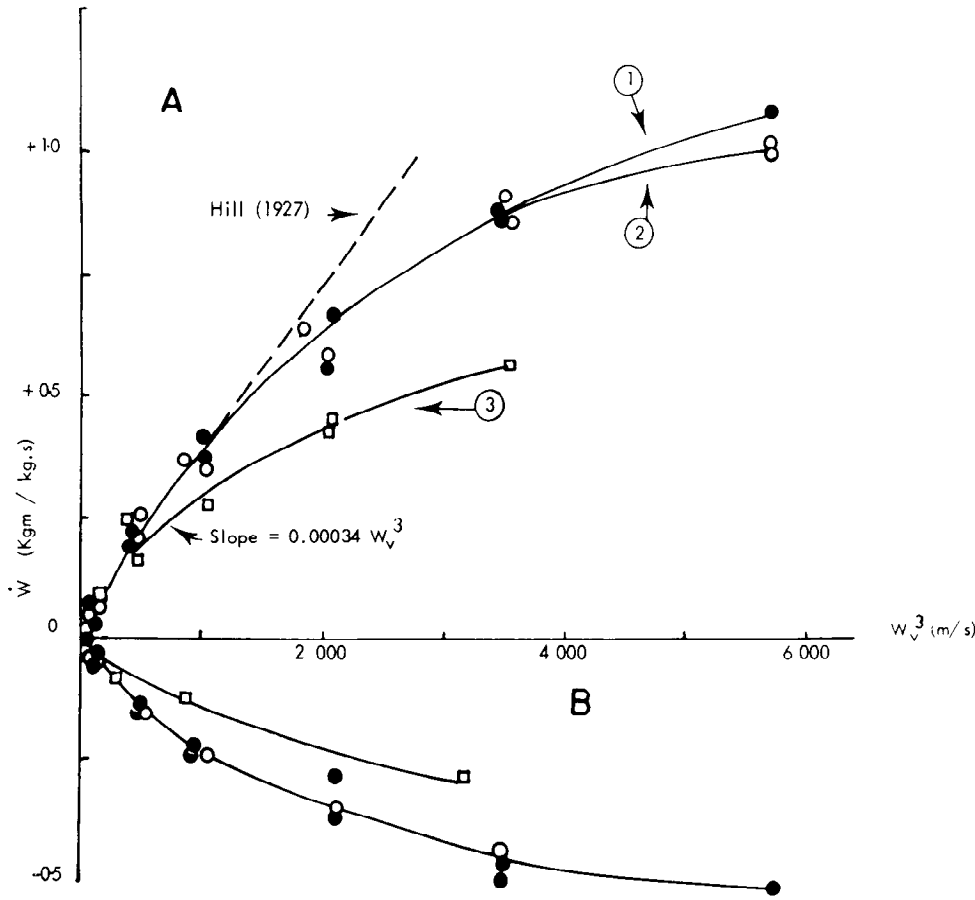
FIG. 4. Work required either to overcome (A) or to resist (B) air velocity. Work ($\dot{W}$) has been expressed in terms of kilogram-meters per kilogram of body weight per second and air velocity as W_V^3. Data (- - -) taken from Hill (8) are shown (see text).

FIG. 5. Change in aerobic cost ($\Delta\dot{V}_{O_2}$) of running uphill and downhill at different speeds on a motor-driven treadmill. Work ($\dot{W}$) with and against gravity is expressed in kilogram-meters per second. Symbols as Fig. 3.

However, beyond a W_V equivalent to ~12 m/s the apparent $\dot{W}$ diminishes and the complete relationship between $\dot{W}$ and W_V^3 over the range of W_V studied in this investigation is better described by the following quadratic equations ($P < 0.001$)

$\dot{W}$ (kg·m·kg^{-1}·s^{-1})

$= 0.00034\ W_V^3 - 0.029 \times 10^{-6}\ (W_V^3)^2;\qquad r = +0.986$

Gradient running at minimal W_V. The results for gradient running at the same values of V as for the "wind" experiments, but with $W_V < 1$ m·s^{-1} are shown in Fig. 5. The data have been plotted in terms of $\Delta\dot{V}_{O_2}$ (calculated from a base line of running for a given V at zero gradient) against the lifting work ($\dot{W}$, kg·m·s^{-1}) performed. For all three subjects during uphill the $\Delta\dot{V}_{O_2}/\dot{W}$ relationship was linear up to levels of work
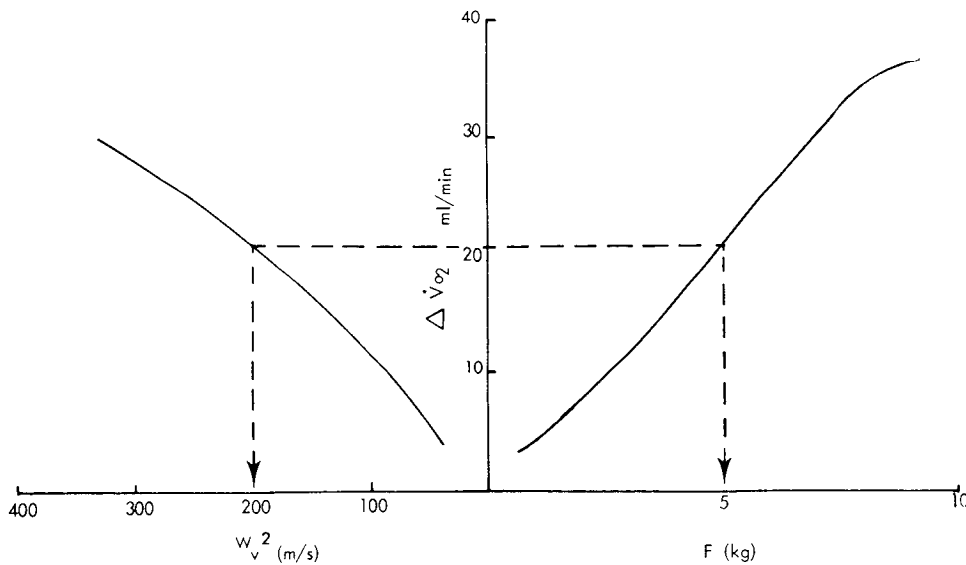
FIG. 6. Change in oxygen intake ($\Delta\dot{V}o_2$, ml·kg^{-1}·min^{-1}) against W^2_V (see Fig. 3) and horizontal component of force (F) for work against gravity (see Fig. 5). Data shown are for *subj 2*. Values of F for each subject were estimated in this way for W_V above and below 15 m·s^{-1} and plotted against W^2_V. Calculated regression (α) coefficients are summarized in Table 1.
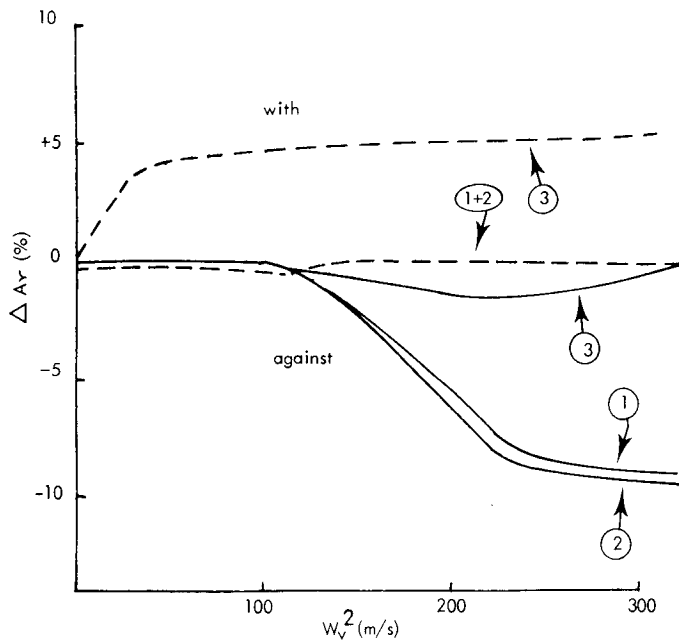

FIG. 7. Percent change of projected area (A_r) with increasing W^2_V. Mean values for 3 subjects.

TABLE 2. *Work efficiency of subjects*

W_V, m·s^{-1}	Subj No.	A_r, m^2	A_r/A_D	A_r/H^2	α, kg·W^2_V	C_D
1–15	1	0.456	0.256	0.153	0.026	0.91
	2	0.475	0.253	0.138	0.026	0.88
	3	0.430	0.242	0.136	0.022	0.82
Mean		0.454	0.259	0.142	0.024	0.87
>15	1	0.417	0.234	0.140	0.019	0.73
	2	0.432	0.230	0.126	0.015	0.56
	3	0.428	0.241	0.135	0.011	0.42
Mean		0.425	0.235	0.133	0.015	0.57

Values are given for the projected areas (A_r) in relation to body surface area (A_D) and body height squared (H^2) together with the drag coefficients (C_D) for running against wind velocities above and below 15 m·s^{-1}. α is the regression coefficient for the slope of the F/W^2_V relationship for 3 subjects (see METHODS).

demanding $\dot{V}o_{2\,max}$ and was independent of V. During downhill running the increase in $\Delta\dot{V}o_2$ was reduced and beyond a negative W of ~15 kg·m·s^{-1} the slope of the $\Delta\dot{V}o_2/W$ line diminished markedly, though as with positive work the association between the two variables was unaffected by V.

Projected areas and drag coefficients. The data given in Figs. 3 and 5 allow calculation of the total F opposing the runner if comparison is made at the same V (Fig. 6). The resulting slope of the F/W^2_V gives an estimate of α for human subjects and thus allows the C_D to be calculated (see METHODS, *Eq. 1*) for the three subjects at W_V above and below 15 m·s^{-1} (see METHODS and Table 1) provided the projected areas (A_r) are known. The changes of A_r with W_V are shown in Fig. 7 and the mean C_D data at high and low W_V are summarized in Table 2.

Apparent efficiency of work with and against wind and gravity. To calculate the apparent efficiency of work

with and against the wind, the forces acting on the body must be visualised [cf. Margaria et al. (10)] as either facilitating or retarding progression. For example, a force of (say) 5 kg exerting a backward pull on a 100-kg man will be equivalent to him traversing a hill with a 1:20 slope or exercising on a treadmill inclined at a gradient of 5%. Thus, on the basis of Hill's original equation and if correction is made for the changes in A_r (Table 2, Fig. 7), the W^2_V can be expressed as an equivalent gradient. On this basis the relationship between the change of energy cost (ΔE, cal·kg^{-1}·m^{-1}) of uphill and downhill running and exercising with and against different air velocities is shown in Fig. 8.

DISCUSSION

The consistency of the oxygen cost of running results and their agreement with previous published work (5) are regarded as evidence of the accuracy of the $\dot{V}o_2$ measurements and the calibration and recording of airflows in the wind tunnel. The reproducibility of the data also overcomes the possible criticism that two different treadmills were used in the present investigation (Fig. 1). The projected areas (A_r) and drag coefficient (C_D) of the
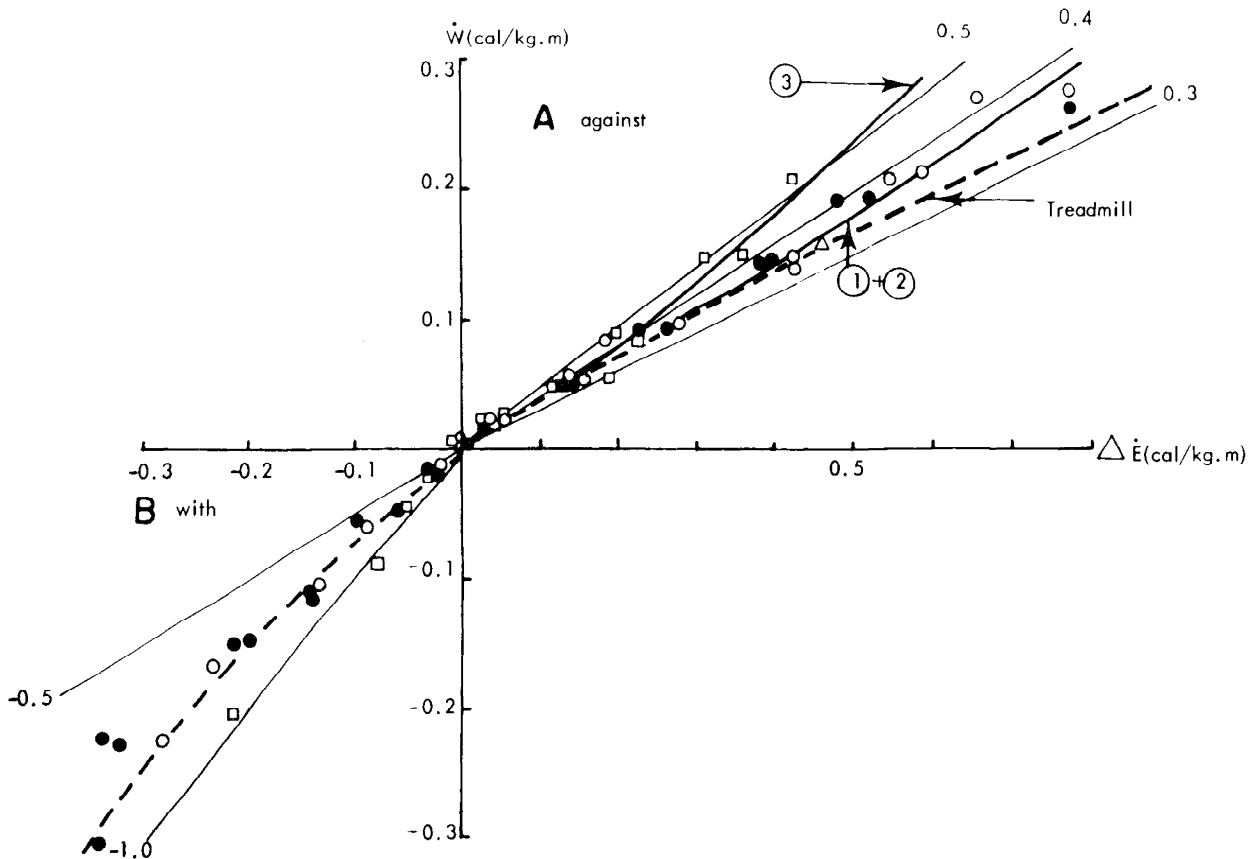
FIG. 8. Comparison between change of energy cost (E, cal·kg^{-1}·m^{-1}) between uphill and downhill treadmill work (– – –) and running against and with a wind (subject symbols as in Fig. 3). Wind velocity has been expressed as an equivalent gradient (see text).

subjects during the running experiments show close agreement with Hill's (8) original observations on an 8-in. model in the wind chamber at the National Physical Laboratory. He found that A_r in the running posture varied as 0.146 of the model's height (H) to the second power and the C_D from his data can be calculated as 0.9, which compares favorably with the mean values of 0.143 and 0.89, respectively, found in the present investigation (Table 1). Pugh (14) found A_r to be 0.266 times the body surface area (A_D); the value for this study is 0.251. The corresponding ratio for A_r to H^2 and A_D for running with the wind for which, to the author's knowledge, no previous data are available, are 0.147 and 0.259.

The energy expended to overcome air resistance at W_V <15 m·s^{-1} is closely in agreement with that given by Hill (8) and from the data given in Table 2 the following equation, which represents the horizontal force (F) acting on the body (at <15 m·s^{-1}), can be derived: F = 0.024 W_V^2; or if A_r is taken into account, F = 0.053 W_V^2 A_r. The equation is approximately the same as Hill's and is consistent with some earlier observations reported by du Bois-Reymond (1). At high airflows the present data find some agreement with those of Pugh (13, 14), but there are fundamental differences between his work and this investigation. Pugh concluded from the results of this study that the change in energy cost of running against different W_V was dependent on V and that exercise on a gradient was always less efficient than the "equivalent" work against air resistance. His observations are difficult to reconcile with the data given in Figs. 2–4 and 8.

Provided W_V does not exceed 15 m·s^{-1} a precise equivalence can be drawn between horizontal and vertical forces: the increased (or decreased) O_2 cost per kilogram body weight and per meter of distance covered is the same and independent of V. The subject exercised with the same "apparent" and net mechanical efficiencies in both situations. The lack of association between $\Delta\dot{V}o_2$ and V is not difficult to appreciate during treadmill work at different W_V, because in this form of exercise the effective (forward) speed of progression is zero. At minimal airflow all the energy consumed is utilized as internal work raising and lowering the center of gravity and altering the kinetic state of the limbs and little or none appears as external (useful) work. Thus an increase in treadmill speed (V) would be expected to effect an overall rise in the aerobic energy cost of running, but this should not affect that portion necessary to overcome a given W_V provided A_r is unchanged, the $\dot{V}o_{2\,max}$ of the subject is not exceeded, and the runner's style remains constant. The present results suggest that these conditions are met except at the highest wind velocities.

At W_V > 15 m·s^{-1}, the $\Delta\dot{V}o_2/W_V^2$ relationship appears to depart from linearity (Fig. 3) and there is an apparent decrease in C_D (Table 2). These changes are associated with a reduction in A_r (Fig. 7) but the change is small (~10%; Fig. 7). A reduction of this order of magnitude would account for ~7% change in drag (D). The estimated change in D is of the order of 60% (Table 2). The influence of $\dot{V}o_{2\,max}$ on the $\Delta\dot{V}o_2/W_V^2$ relationship is more difficult to assess. Undoubtedly it has a confounding

influence on the results of *subject 3* (see Figs. 3, 4, and 8). It must be appreciated that running on the treadmill at the slowest speed (8.3 km·h^{-1}) at which it is more efficient to run than walk (2) demands an energy expenditure of at least 35 ml·kg^{-1}·min^{-1}. Against a W_V of 18 m·s^{-1} the added aerobic cost is 30 ml·kg^{-1}·min^{-1} (Fig. 3). Thus, even at modest treadmill speeds against an increasing W_V, the $\dot{V}o_{2\,max}$ of most subjects is rapidly achieved. *Subject 3* ran at 11.3 and 12.9 km·h^{-1}, respectively, and clearly reached his $\dot{V}o_{2\,max}$ at the higher W_V. *Subject 3* also differed in two other respects from his more athletic counterparts. He was less efficient at level running and even at minimal W_V his natural style incorporated a forward flexion of the upper body. The small change of his A_r with increasing W_V can be noted in Fig. 7. His smaller range and increase in $\Delta\dot{V}o_2$ (Fig. 3) certainly contributed to his "apparent" increased efficiency of running against the wind (Fig. 8) but his different running style may (for reasons given below) have been an equally decisive factor.

Subjects 1 and *2* were characterised by high $\dot{V}o_{2\,max}$ values and the leveling off of $\Delta\dot{V}o_2$ with increasing W_V occurred (for them) at submaximal aerobic work levels (Fig. 2). However, at high W_V the two subjects radically changed their running styles and adopted a body posture more similar to that described for *subject 3* at lower W_V. They lowered their heads, changed their (upper) body angle, and leaned into the wind. Thus, as well as reducing A_r as noted above, they were probably able to convert potential drag to body lift. This would have the effect of decreasing both the positive and negative done within each stride (9) and thereby reduce the energy cost. At the highest W_V studied the increased lift was subjectively noticeable and the two subjects reported a feeling of flying between strides and being raised on their toes so that the normal heel-toe contact of running was diminished. A conversion of drag to lift would be expected to reduce aerobic cost both directly and indirectly. The direct effect would be expected to reduce C_D (Table 2) and the increased bounce of the body may contribute indirectly to the amount of work that can be performed by muscles (without recourse to aerobic metabolism) due to phenomenon of elastic recoil (3), which is known to occur at high running speeds or in conditions of excessive body lift.

Running with a W_V produced opposite results to those found against a wind but the reduction in energy cost was much less for a following wind than the increase found for a head wind (Fig. 3). For example, with a head W_V at 15 m·s^{-1}, $\Delta\dot{V}o_2$ was 24.4 ml·kg^{-1}·min^{-1} compared with -11.9 with the same following wind, a saving of approximately 50% of the expected value. Again the reasons are clear: on a motor-driven treadmill the wind will only assist the runner to a certain limited extent. As the wind velocity increases beyond the speed of the treadmill belt the runner will have to brake progressively to maintain his position on the mill and the proportion of negative work within each stride will increase. Thus, working with a following wind is precisely analogous to downhill (negative work) running on a treadmill in calm air.

In outdoor running of course conditions will be differ-

ent to those experienced using a treadmill in a wind tunnel. The runner's motion is relative to the surrounding air so that even on a calm day the extra energy cost (above that which is necessary for speed maintenance) due to air resistance will be proportional to his velocity (V) raised to the second power. Using this approach, the estimated extra energy cost of overcoming air resistance in outdoor track running has been calculated to be 4% at middle distance (6 m·s^{-1}) and 7.8% at sprint (10 m·s^{-1}) speeds. At marathon speeds the maximum effect will be approximately 2% for the elite runners and virtually negligible for times outside 2.5 h. The results may therefore help to explain why McKiken and Daniels (11; see Fig. 1) in contrast to Pugh (13) have failed to find a difference between the energy cost of running indoor and outdoor over the normal range of running speeds (2–5 m·s^{-1}). However, though the aerobic energy effects of running against a wind are small over the normal physiological range, they may nevertheless be important in terms of physical performance, and it is perhaps instructive to examine them not in terms of cost but time.

In the 100-m sprint event, for example, the total energy requirement is for acceleration at the start of the race to overcome inertial forces, speed maintenance, and finally wind resistance. During the first 2–3 s of the race the velocity of the runner is lower, and thus the wind resistance will have relatively little influence compared with the last 60 m. If resistance could be removed completely, it would be equivalent to running on the level compared with a gradient of 4%. The minimum time for an elite (10 m·s^{-1}) athlete would be decreased by approximately 0.25–0.5 s. In the marathon event (best recorded time, 2 h 8 min 33.6 s), the air resistance on a calm day is equivalent to a slope of ~1%; if this was abolished the athletes' speed would be expected to increase by 0.82 km·h^{-1}. This would reduce his time by over 5 min!

The effects of a following wind for reasons outlined will have approximately half the effect, though presumably unlike the treadmill a low air speed will assist the forward velocity of the runner outdoor. However, once the following wind exceeds the velocity of the runner, he would have to perform an increased amount of negative work in the latter half of each stride to maintain his running posture. Thus, when running on an oval track on a windy day, an athlete will find it difficult to achieve his best performance. The extra energy expended against the wind (say) in the back straight will not be compensated by an equal gain in the home straight. If for example we have a wind blowing (W_V) down the track equal to the runners speed (V) in a middle-distance race (6 m·s^{-1}), in the back straight the backward pull on the athlete's body will be approximately 3.8 kg, equivalent (for a 65-kg athlete) to running up a gradient of 5.8%. This will increase his oxygen cost by a ~4 ml·kg^{-1}·min^{-1} or reduce his speed by 1 km·h^{-1}. In the home straight his forward speed will be equivalent to the W_V and this resistance to progression theoretically zero. To compensate for the extra energy expanded in the back straight he would need W_V of at least 15 m·s^{-1}. Athletes are also sensitive to cross winds and running the bends with W_V at right angles to the runner would also be expected to increase energy expenditure. Hill (8) has

suggested that where $W_V = V$ the extra cost of running the crown of the bend will (paradoxically) be 1.41 times greater than the head resistance, i.e., $\sqrt{(1 + W_V^2)/(V^2)}$. Thus the overall effect on performance would likely to be an increase in time of approximately 4 s per lap. A race on a track under such windy conditions would be similar to an undulating course experienced by cross-country and long-distance road running athletes. On a calm day, the relative air velocity will be equivalent to the runners' speed (6 m·s^{-1}) at every point on the track if air resistance could be eliminated the performance time (using the same argument as above) would be decreased by 1.6 s per lap. Clearly the most sensible way for an athlete to run a race on an oval track on a calm or windy day is to shield behind a front runner until the closing stages of the race. We performed some crude shielding experiments in the wind tunnel and they gen-erally confirmed the results reported by Pugh (14). The actual magnitude of effect was solely dependent on the proximity of the two runners. On the treadmill it was quite easy to reduce the effects of air resistance by at least 80–85% by shielding. If these data are applied to a track race on a calm day at a V of 6 m·s^{-1}, then the saving in time would be approximately 1 s per lap. As pointed out by Pugh (14), this is in accord with common observations and experience of middle-distance runners.

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