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Gross Energy Cost of Horizontal Treadmill and Track Running

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Summary

The gross energy cost of treadmill and track running is re-investigated from data published in the literature. An average equation, weighted for the number of subjects in each study, was found:

$$\dot{V}O_2 \text{ (ml/kg/min)} = 2.209 + 3.163 \text{ speed (km/h)}$$

for 130 subjects (trained and untrained males and females) and 10 treadmill studies. On the track, wind resistance as predicted by Pugh (1970) was added to the treadmill cost of running and yielded the following equation for adults of average weight and height:

$$\dot{V}O_2 = 2.209 + 3.163 \text{ speed} + 0.000525542 \text{ speed}^3$$

Between 8 and 25 km/h, the following linear equation:

$$\dot{V}O_2 = 3.5 \text{ speed (or met = km/h)}$$

was very close to the cubic equation. This linear equation for track running is, however, different from the treadmill linear equation, particularly for speeds over 15 km/h. This equation is also slightly different from the one published by Pugh (1970) for track running from 7 trained subjects only.

Studies on the gross energy cost of flat running on a treadmill are numerous (table I). On a track, Maksud et al. (1971), McMiken and Daniels (1976) and Pugh (1970, 1971) appear to be the only ones to have studied the gross energy cost of flat running as well as air resistance. In an attempt to standardise the energy cost of running, the American College of Sports Medicine (ACSM, 1975, 1980) published values that were, however, different in 1975 and 1980 (table I). The ACSM also attributed the same energy cost values to horizontal running on a treadmill as to running on a hard surface. The origin of the ACSM data was not mentioned (i.e. number and type of subjects, references). In view of the large interindividual and interstudy variations in the energy cost of flat treadmill running (i.e. ≈ 10 ml/kg/min; fig. 1) and in view of the small number of subjects in each of these studies (table I), particularly for Pugh's study on track running (7 trained subjects), an analysis of these curves was made in order to find out the most probable curves for horizontal treadmill and track running.

1. Methods of Establishing Gross Energy Cost

The probable gross energy cost curve for horizontal treadmill running was established by averaging the intercept and slope coefficients of the published regressions (table I) taking into consideration the number of subjects in each study. Thereafter, the net energy cost of air resistance

(Pugh, 1970, 1971) was added to the probable gross energy cost of treadmill running to obtain the probable gross energy cost of track running.

2. *Treadmill Running and Gross Energy Cost*

Weighted analysis of the gross energy cost of horizontal treadmill running (table I and fig. 1), yielded the following regression:

$$\dot{V}O_2 = 2.209 + 3.1633\ V \qquad \text{(Eq. 1)}$$

where $\dot{V}O_2$ = oxygen uptake (ml/kg/min)

V = running speed (km/h)

This regression comes from 10 studies for a total of 130 subjects, males (71.5%) and females (28.5%), trained (50%), untrained (31.5%) and unknown training status (18.5%).

The usefulness of a generalised equation is to provide an unbiased estimate of the average energy cost of running at a particular speed. Obviously the interindividual variations appear quite large, larger than the ± 5% variation often reported for walking and running (Wyndham, 1967). This value is derived from the study of homogeneous groups of subjects (age, sex and training status). The plotting of curves from different studies (fig. 1) using different groups of subjects indicates a 10 ml/kg/min range in the energy cost of running at any speed (fig. 1). Also the standard deviation obtained by averaging the intercept of the 15 subgroups of subjects (table I) is 8.3. Although the intercept of each regression is, in fact, directly related to the slope of the regression, this large value confirms the importance of the interstudy and interindividual variations in the energy cost of running and suggests that the average estimate should be carefully handled and interpreted.

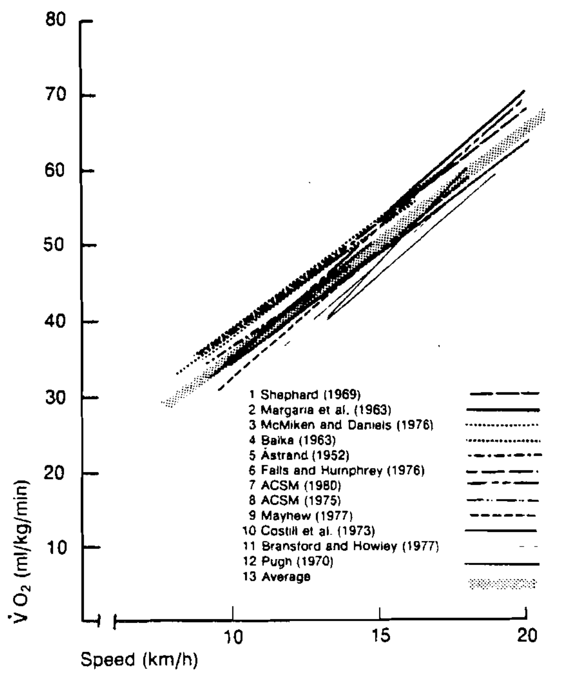

Fig. 1. Gross energy cost of horizontal treadmill running according to various studies (table I). Wide curve is a weighted average curve: Y = 2.203 + 3.163 X.

The intercept standard deviation of 8.3 and some reported intercepts (table I) indicate a negative intercept as normal. This does not imply a negative oxygen uptake for the subject standing still (i.e. running speed = 0 km/h). In fact, minimal running speed is set at 8 km/h. Below that speed, subjects begin to walk. In other words, the regressions presented in this review are only valid for the range of running speeds usually encountered in the reported studies, i.e. 8-20 km/h (see fig. 1).

In order to reduce the variability, it appears necessary to determine specific regressions according to the status of the subject. However, data are scarce or confusing. For example (table I), Bransford and Howley (1977) demonstrated that both trained and untrained females are less efficient than trained and untrained males, but data reported by Falls and Humphrey (1976) on untrained females indicate similar efficiency to untrained males (Balke, 1963; Shephard, 1969). Åstrand (1952) also reported similar efficiency in males and females with presumably similar training status. Thus, from so few studies using small groups of subjects, it is difficult to come to any conclusions about any sexual difference in the energy cost of horizontal running. For inclined walking on the treadmill, Bruce et al. (1973), using large groups of subjects (n ⩾ 200), reported regressions that show better efficiency in females as compared to males, but inclined walk-

Table I. Gross energy cost regressions for horizontal treadmill running[1]

Reference	No. of subjects	Sex[2]	Training level[3]	$\dot{V}O_2$ = a + b speed	
				a	b
ACSM (1975)[4]	?	?	?	5.25[4]	3.0625[4]
ACSM (1980)[4]	?	?	?	3.275[4]	3.3478[4]
Åstrand (1952)	10	F	?	10.2	2.61
	9	M	?	9.33	2.93
Balke (1963)	5	M	?	10.2	2.86
Bransford and Howley (1977)	10	F	U	10.942	2.517
	10	F	T	3.511	3.033
	10	M	U	−0.510	3.40
	10	M	T	−3.562	3.383
Costill et al. (1973)	16	M	T[5]	−15.24	4.20
	6	M	T[5]	−5.24	3.4
Falls and Humphrey (1976)	7	F	U	8.66	2.92
Margaria et al. (1963)	2	M	T	3.5	3.33
Mayhew (1977)	9	M	T	−0.82	3.318
McMiken and Daniels (1976)	8	M	T	5.363	2.867
Pugh (1970)	4	M	T	4.245	2.979
Shephard (1969)	14	M	U	7.6	2.98
Total	130	MF	TU		
Mean				2.209	3.163
Standard deviation				8.285	0.474

[1] $\dot{V}O_2$ is in ml/kg/min, and speed in km/h.
[2] M = male (n = 93); F = female (n = 37).
[3] U = untrained (n = 41); T = trained (n = 65); ? = unknown status (n = 24).
[4] Values excluded from the weighted mean.
[5] Endurance runners (n = 16) and marathoners (n = 6).

ing is different from horizontal running. Nevertheless, and based on dimensional laws (Åstrand and Rodahl, 1970) $\dot{V}O_2$ is a measure of power and, as such, should be best expressed in ml/kg$^{2/3}$/min instead of ml/kg/min in order to be weight independent. Expressing $\dot{V}O_2$ in ml/kg/min results in lower values for heavier males than lighter females indicating an apparent but unreal higher efficiency at submaximal speeds or lower $\dot{V}O_{2max}$. To experimentally demonstrate these dimensional laws, a wide range of bodyweight is necessary (Kleiber, 1947). Differences between male and female adults might be too small to be demonstrated and use of a single equation thus appears justified.

Trained subjects appear to be more efficient than untrained ones (table I), but it is difficult to estimate specific regressions with the data available; data for trained females and untrained males are based on one or two studies only, and data from trained males indicate considerable variation in the efficiency of running. The trained runner is sometimes efficient and sometimes not. Thus, specific regressions for trained and untrained runners would be useless.

The generalised regression presented in this review is derived from adult data and appears to be valid for adults only. Children appear to be less efficient than adults in running (Åstrand, 1952; Daniels et al., 1978; Davies, 1980; Mercier et al., 1983; Pate, 1981; Silverman and Anderson, 1972). An analysis of the studies reported above indicates a 2% increase in the gross energy cost of running for each year of age from 18 years to 8 years. This figure is a gross estimate, since none of the studies were designed to systematically quantify the effect of age on the energy cost of horizontal treadmill running.

Some valuable studies were excluded from computation of the generalised equation. Van der Walt and Wyndham (1973) proposed an equation where the O_2 cost of running is a square function of the speed. This is not supported by any of the 12 studies reported in table I. It is, however, worthwhile to point out that their proposed curve falls in the middle of the linear ones (fig. 1). Wyndham et al. (1971) also presented data for 3 running velocities in a very close range. These data are consistent with the others (fig. 1), but the derived equation was so unrealistic that it could not be included in the computation of a generalised equation. Similarly, no fair regression could be estimated from data reported by Hogberg (1952) on 1 subject at 2 running speeds only. Maksud et al. (1971) reported data on 15 subjects tested at 11.3, 16.1 and 19.3 km/h both on the treadmill and the track, but their original data, when transformed to ml/kg/min from L/min using the average weight of the subjects, were suspiciously low and thus were discarded from the present analysis. Data reported by Dill (1965) on 3 subjects expressed the O_2 cost of running in ml/kg/min. The estimated cost in ml/kg/min appears very similar to the other studies (fig. 1). Thus, the generalised regression (equation 1) for treadmill running appears consistent with the literature.

3. *Track Running and Energy Cost*

The net energy cost of running against air resistance is calculated according to Pugh (1970, 1971):

$$\Delta \dot{V}O_2 = 0.00354 \text{ Ap } V^3 \qquad \text{(Eq. 2)}$$

where $\Delta\dot{V}O_2$ = net oxygen uptake (L/min)
Ap = projected area while running (m^2)
V = running and wind speed (m/s)

Projected area while running could be estimated from body surface area (Ap = 26.6% SA; Pugh, 1970). Body surface area (m^2) could be estimated from the weight (kg) and height (cm) using the Dubois formula ($SA = W^{0.425} \times H^{0.725} \times 0.007184$; Consolazio et al., 1963). As the interindividual variations in projected area only have a negligible effect on the gross energy cost of running expressed in ml/kg/min, an average value (males and females combined) could be used to establish a simplified regression for track running (equation 1 + equation 2). Height and weight norms in North America (Demirjian, 1980) indicate average values of 175 and 160cm and 75 and 60kg for males and females, respectively, which yield combined values of 168cm and 68kg, a surface area of $1.77m^2$ and a projected area of $0.471m^2$ while running.

Changing units and considering the projected area as a constant (Ap = 0.471 m^2), equation 2 becomes:

$$\Delta\dot{V}O_2 = 0.000525542 \; V^3 \qquad \text{(Eq. 3)}$$

where $\Delta\dot{V}O_2$ = net oxygen uptake (ml/kg/min)
V = running and wind speed (km/h)

Equations 2 and 3 are valid only in calm air when wind and running speeds are equal (otherwise: $V^3 = V \text{ running} \times V^2 \text{ wind}$).

The gross energy cost of track running could thus be established by adding equations 1 and 3:

$$\dot{V}O_2 = 2.209 + 3.163 \; V + 0.000525542 \; V^3 \qquad \text{(Eq. 4)}$$

From the equation, it can be seen that $\dot{V}O_2$ of track running is a cubic function of the running speed. Because the effect of wind resistance is increasingly small for human running speeds below 25 km/h, and because it is not easy to use the equation in the reverse way (i.e. calculate V from $\dot{V}O_2$), it is worthwhile to seek simplified regressions (second or first degree polynoms). For instance, a second degree polynom was calculated by the least squares method from the calculated values with equation 3 for the following speeds: 10, 12, 14, 16, 18 and 20 km/h:

$$\dot{V}O_2 = -0.856 + 0.0122586\ V^2\ (r = 0.996)\text{(Eq. 5)}$$

Then, the gross energy cost of track running could be established by adding equations 1 and 5:

$$\dot{V}O_2 = 1.353 + 3.163\ V + 0.0122586\ V^2 \quad \text{(Eq. 6)}$$

Equation 6, a second degree polynom, and easier to manipulate, is very similar to equation 4, a third degree polynom, between 8 and 25 km/h (fig. 2).

Since the wind resistance effect is very small for middle and long distance running speeds, a first degree polynom was also calculated by the least squares method from the calculated values with equation 4 for the following speeds: 8, 10, 12, 14, 16, 18, 20 and 25 km/h:

$$\dot{V}O_2 = -2 + 3.6\ V\ (r = 0.9992) \quad \text{(Eq. 7)}$$

Furthermore, it is interesting to note that equation 7 is not visually different from the simple equation 8 (fig. 2):

$$\dot{V}O_2 = 3.5\ V \quad \text{(Eq. 8)}$$

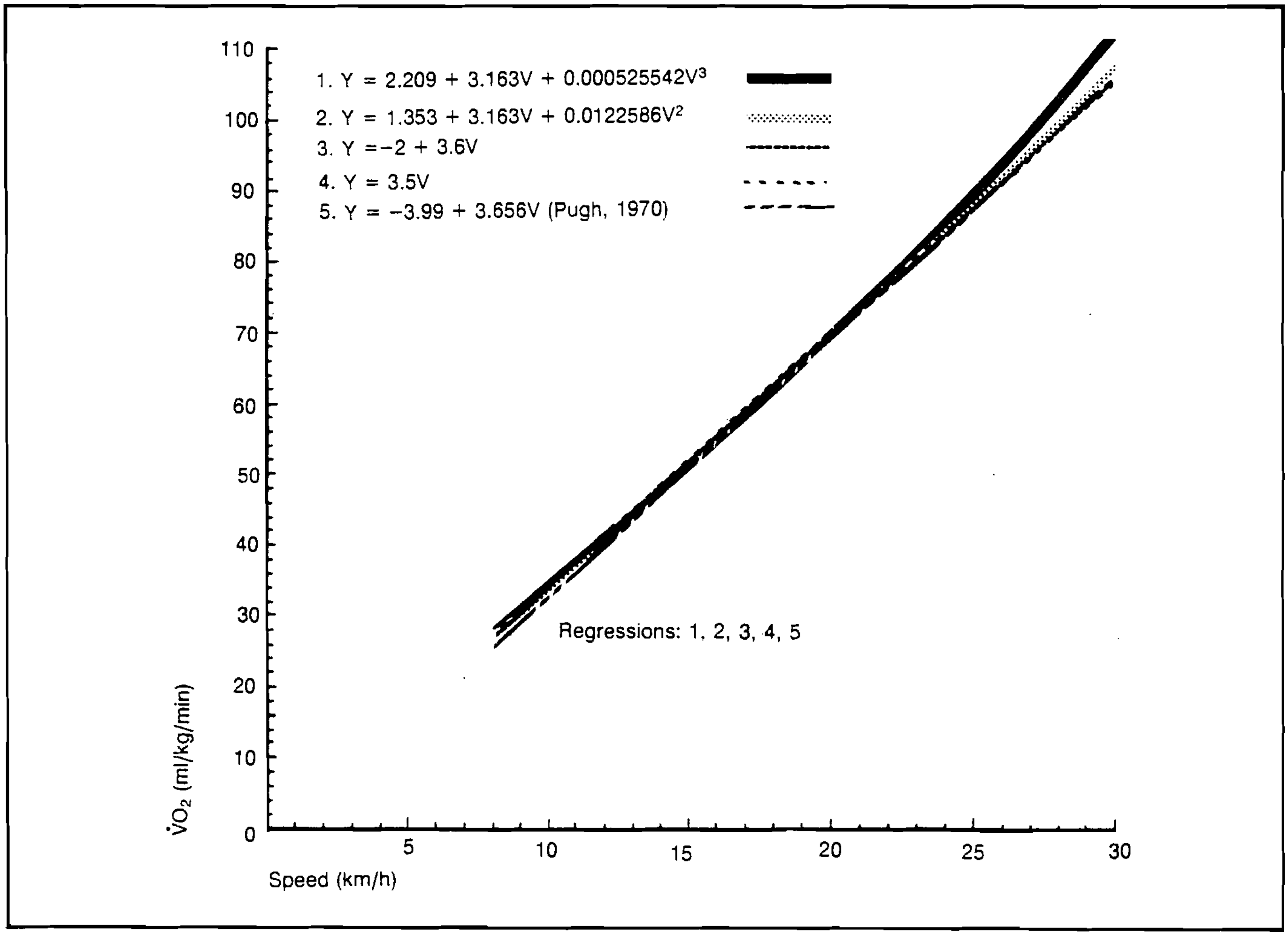

Fig. 2. Gross energy cost of track running in calm air using different approaches: Curve 1, third degree polynom obtained by adding the net energy cost of running against air resistance to the gross energy cost of horizontal treadmill running. Curve 2, second degree polynom obtained by least squares approximation of curve 1. Curve 3, first degree linear polynom obtained by least squares approximation of curve 1. Curve 4, arbitrary simplification of curve 3. Curve 5, direct measurement on 7 trained subjects (Pugh, 1970)

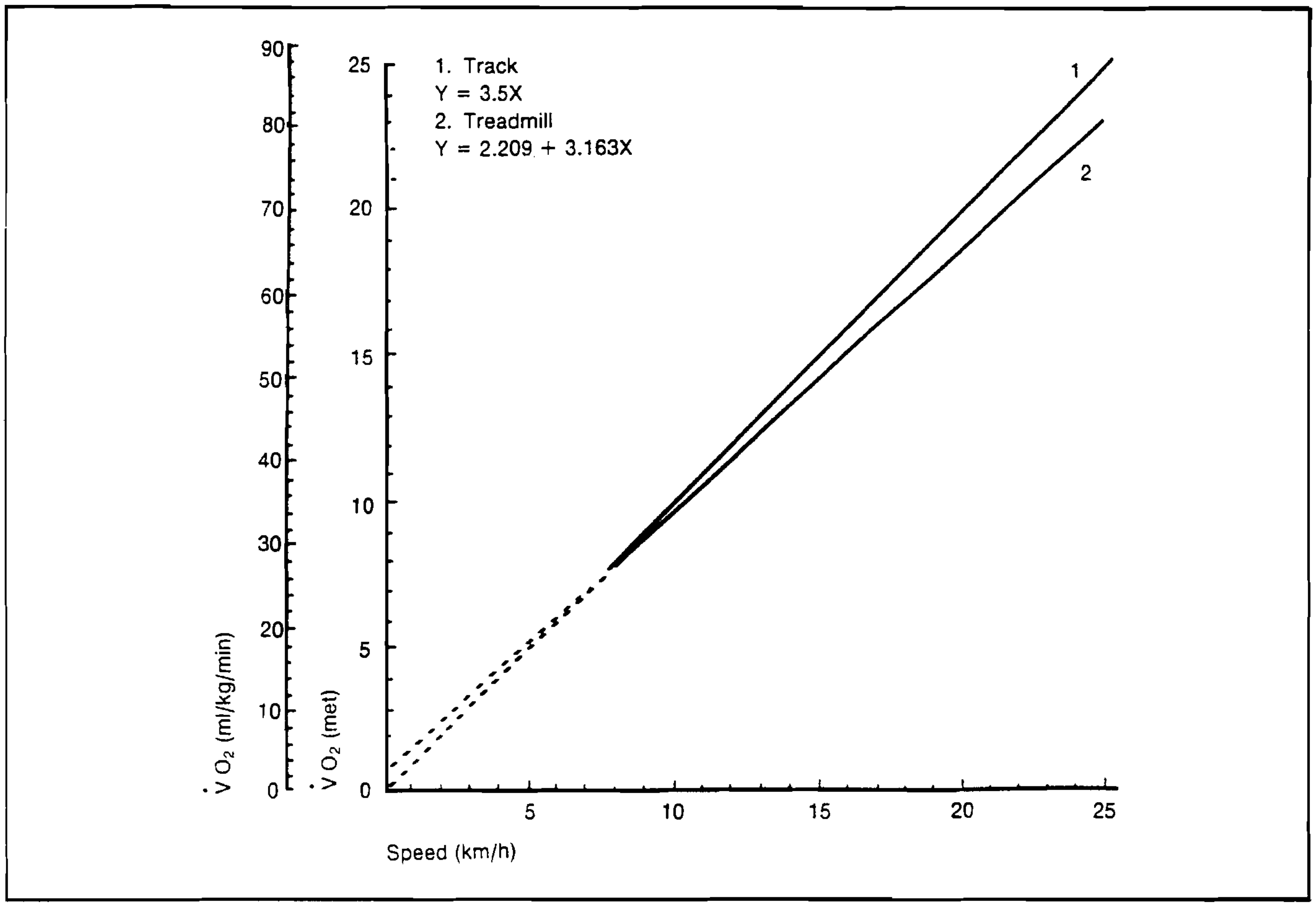

Fig. 3. Gross energy costs of horizontal treadmill running and track running in calm air. Wind resistance cost, almost negligible between 8 and 15 km/h is 6.2 ml/kg/min at 25 km/h. Above 25 km/h, the gross energy cost of track running is better estimated by $Y = 2.209 + 3.163\,X + 0.000525542\,X^3$.

It is interesting to note that for track running, equation 8 becomes $\dot{V}O_2 = V$, when $\dot{V}O_2$ is expressed in met (1 met = 3.5 ml/kg/min; ACSM, 1975, 1980) and V in km/h. The simplicity and accuracy of equation 8 justify its use for middle and long distance running speeds. It is also interesting to note that equation 8 is very similar to the one obtained by Pugh (1970) with the direct measurement of $\dot{V}O_2$ on 7 trained subjects running on a track:

$$\dot{V}O_2 = -3.99 + 3.656\ V \qquad \text{(Eq. 9)}$$

The number and the trained status of subjects used by Pugh (1970) may explain the slightly lower energy cost of equation 9 as compared to those of equations 4, 6, 7 or 8 (fig. 2), as expected by comparing published curves for trained and untrained subjects (table I and fig. 1). It is, however, fortunate that the difference is not as large as the one seen for some published curves for treadmill running with trained subjects (Bransford and Howley, 1977; Costill et al., 1973; Mayhew, 1977; see table I and fig. 1).

McMiken and Daniels (1976) reported a single regression for track and treadmill running but their investigated range of speeds was small and situated at the slower end (i.e. 10 to 16 km/h). Data reported by Maksud et al. (1971) appear more conflicting with very low O_2 cost compared with the proposed equations (equations 4, 6, 7 and 8), and to Pugh (1970; equation 7) and to McMiken and Daniels (1976; table I). No explanation for this discrepancy is readily available.

4. Treadmill and Track Running

The fact that equations 7 or 8 are linear does not imply that air resistance was not considered. In fact, proposed equations 1 and 8 for treadmill (no air resistance) and track running (air resistance) are quite different (fig. 3). Below 16 km/h, however, air resistance is very small which is concordant with the work of Pugh (1970, 1971), Maksud et al. (1971) and McMiken and Daniels (1976).

5. Conclusion

The analysis of published energy cost curves in the literature has permitted the proposal of distinct and probable curves for horizontal treadmill and track running. It was also found that for speeds between 8 and 25 km/h a very simple linear equation could accurately describe the gross energy cost of track running.

This review has shown wide variations in the energy cost of running from one study to another and, obviously, from one individual to another. Standardised equations, although useful to provide unbiased estimates of the average energy cost of running, are definitely limited in predicting the energy cost of running for one individual. Hopefully, equations developed specifically for males or females and for good or bad runners will soon be available in order to reduce the error of prediction at the individual level.

Acknowledgement

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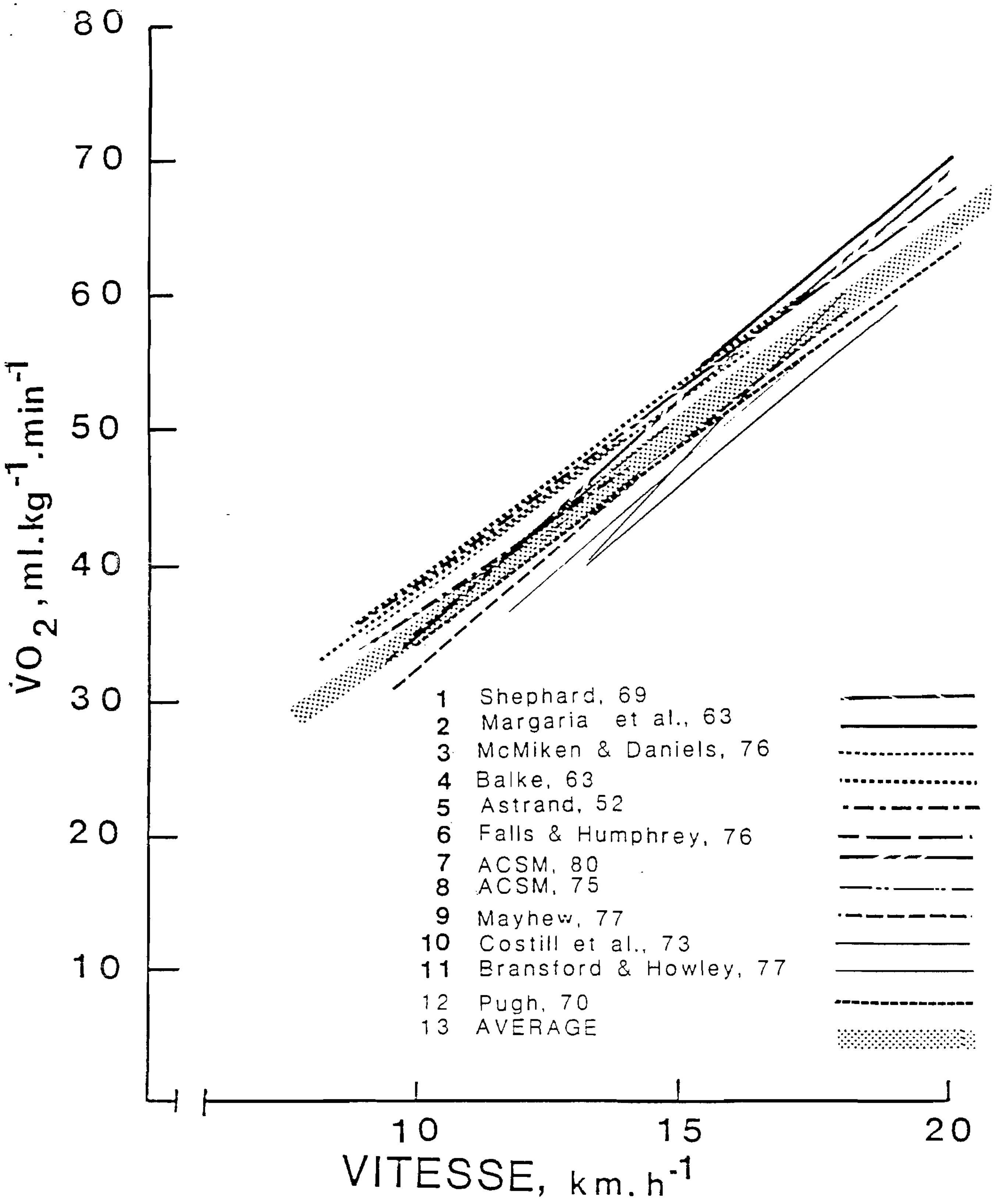
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$\dot{V}O_2$, ml.kg^{-1}.min^{-1}
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VITESSE, km.h^{-1}
1 Shephard, 69
2 Margaria et al., 63
3 McMiken & Daniels, 76
4 Balke, 63
5 Astrand, 52
6 Falls & Humphrey, 76
7 ACSM, 80
8 ACSM, 75
9 Mayhew, 77
10 Costill et al., 73
11 Bransford & Howley, 77
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13 AVERAGE