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Aerobic Performance of Female Marathon and Male Ultramarathon Athletes

C. T. M. Davies and M. W. Thompson

MRC Environmental Physiology Unit, London School of Hygiene and Tropical Medicine, Keppel Street, London, WC1E 7HT, England

Summary. The aerobic performance of thirteen male ultramarathon and nine female marathon runners were studied in the laboratory and their results were related to their times in events ranging in distance from 5 km to 84.64 km.

The mean maximal aerobic power output ($\dot{V}O_{2\ max}$) of the men was 72.5 ml/kg · min compared with 58.2 ml/kg · min ($p < 0.001$) in the women but the O_2 cost ($\dot{V}O_2$) for a given speed or distance of running was the same in both sexes. The 5 km time of the male athletes was closely related to their $\dot{V}O_{2\ max}$ ($r = -0.85$) during uphill running but was independent of relative power output (%$\dot{V}O_{2\ max}$). However, with increasing distance the association of $\dot{V}O_{2\ max}$ with male athletic performance diminished (but nevertheless remained significant even at 84.64 km), and the relationship between %$\dot{V}O_{2\ max}$ and time increased. Thus, using multiple regression analysis of the form:

$$42.2 \text{ km (marathon) time (h)} = 7.445 - 0.0338\ \dot{V}O_{2\ max} \text{ (ml/kg} \cdot \text{min)} - 0.0303\%\ \dot{V}O_{2\ max}\ (r = 0.993)$$

and

$$84.64 \text{ km (London–Brighton) time (h)} = 16.998 - 0.0735\ \dot{V}O_{2\ max} \text{ (ml/kg} \cdot \text{min)} - 0.0844\%\ \dot{V}O_{2\ max}\ (r = 0.996)$$

approximately 98% of the total variance of performance times could be accounted for in the marathon and ultramarathon events. This suggests that other factors such as footwear, clothing, and running technique (Costill, 1972) play a relatively minor role in this group of male distance runners. In the female athletes the intermediate times were not available and they did not compete beyond 42.2 km (marathon) distance but for this event a similar association though less in magnitude was found with $\dot{V}O_{2\ max}$ ($r = -0.43$) and %$\dot{V}O_{2\ max}$ ($= -0.49$). The male athletes were able to sustain 82% $\dot{V}O_{2\ max}$ (range 80–87%) in 42.2 km and 67% $\dot{V}O_{2\ max}$ (range 53–76%) in 84.64 km event. The comparable

Offprint requests to: Dr. C. T. M. Davies (address see above)

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figure for the girls in the marathon was 79% $\dot{V}O_{2\ max}$ (ranges 68–86%). Our data suggests that success at the marathon and ultramarathon distances is crucially and (possibly) solely dependent on the development and utilisation of a large $\dot{V}O_{2\ max}$.

Key words: Aerobic performance – Athletes, marathon, ultramarathon

The physiology of male marathon running has been studied extensively in the laboratory (Costill and Fox, 1969; Costill, 1970, 1972; Costill et al., 1971; Pollock, 1977) and in the field (Pugh et al., 1967; Magazanick et al., 1974; Maron et al., 1976, 1977) but there are few data on women (Wilmore and Brown, 1974; Daniels et al., 1977). However, at distances beyond the traditional marathon (42.2 km) event there have been no systematic observations made on athletes of either sex. Costill and Winrow (1970) reported the metabolic cost of running for 2.5–5.5 h on two middle-aged distance athletes and Dancaster and Whereat (1971) observed fluid balance changes during the comrades (86.9 km) marathon race, but the physiology of ultralong-distance running has not been investigated. The present study is concerned with aerobic performance in the laboratory and field of British male ultra-long-distance and female marathon athletes. The girls were nationally ranked athletes and the men contained the world record holder for the 50 (80.48 km) and 100 (160.93 km) miles and the 3rd ranked athlete at 24 h distance running.

Subjects and Methods

The physical characteristics of the male and female athletes studied are given in Table 1. All the male athletes regularly competed in marathon and ultramarathon races. In addition to CW (world record holder) TO'R was an outstanding ultralong-distance runner having won the prestigous London to Brighton race (84.64 km) in 1976 in 5 h 23 min. TR was the current (1977) Road Runners Club 24 h event champion covering 251.46 km. At the time of testing in the laboratory, all male athletes were in training (120–250 km per week). The best female athlete was LB who had a time for the marathon of 2 h 57 min, though PD and BN were outstanding older ♀ athletes. Like the men they were all in regular training when measured, though their weekly training schedules were less arduous (80–100 km per week).

The oxygen cost of running on the treadmill at various speeds was determined for all athletes using an open circuit technique, collection being made through a modified, low resistance, Otis-McKerrow valva and 1.5″ smooth bore tubing into a conventional Tissot spirometer. The O_2 and CO_2 content of

Table 1. Physical characteristics and maximal aerobic power output ($\dot{V}O_{2\ max}$) of the 13 male and 9 female athletes (Mean ± SD)

	Age (year)	Wt (kg)	Ht (cm)	$\dot{V}_{E\ max}$ l/min	$\dot{V}O_{2\ max}$ l/min	ml/kg · min	$f_{H\ max}$ beats/min
♂	33.0 ± 6.3	63.5 ± 6.9	172.3 ± 8.1	162.5 ± 19.4	4.64 ± 0.48	72.5 ± 3.8	194 ± 10
♀	29.8 ± 7.8[c]	52.3 ± 2.6[a]	162.5 ± 2.2[a]	115.2 ± 12.8[a]	3.04 ± 0.19[a]	58.2 ± 4.8[a]	197 ± 6

♂ ♀ Significance: [a] $p < 0.001$; [b] $p < 0.01$; [c] $p < 0.05$

the expired air was determined by physical gas analysers (Beckman and Servomex Instruments Ltd.) which were regularly calibrated with gases of known concentrations from prior (Lloyd) Haldane chemical analysis. The maximal oxygen intake ($\dot{V}O_{2\ max}$) was either measured on the same or a subsequent occasion (Table 1) using the treadmill and the criteria outlined by Davies (1968). The performance times of the athletes on the track and in competitive road running were obtained by questionnaires and from the official records of the Road Running Club of Great Britain.

Results

The male athletes were heavier, taller, less fat and had higher aerobic power outputs than their female counterparts (Table 1), but despite these differences the O_2 cost of running per kg body weight ($\dot{V}O_2$ ml/kg · min) at various speeds was the same in both groups (Fig. 1). There were no significant differences between either the slopes or the intercepts of the male and female regression lines ($p > 0.1$). The combined regression for the ♂ and ♀ athletes was given by:

$$\dot{V}O_2 \text{ (ml/kg} \cdot \text{min)} = -7.736 + 3.966 \text{ speed (km/h)}; (r = +0.94) (n = 77). \quad (1)$$

The mean $\dot{V}O_{2\ max}$ in the males was 72.5 (± 3.8) ml/kg · min compared with 58.2 (± 4.8) ml/kg · min in the females. The best guide to $\dot{V}O_{2\ max}$ in the males from their

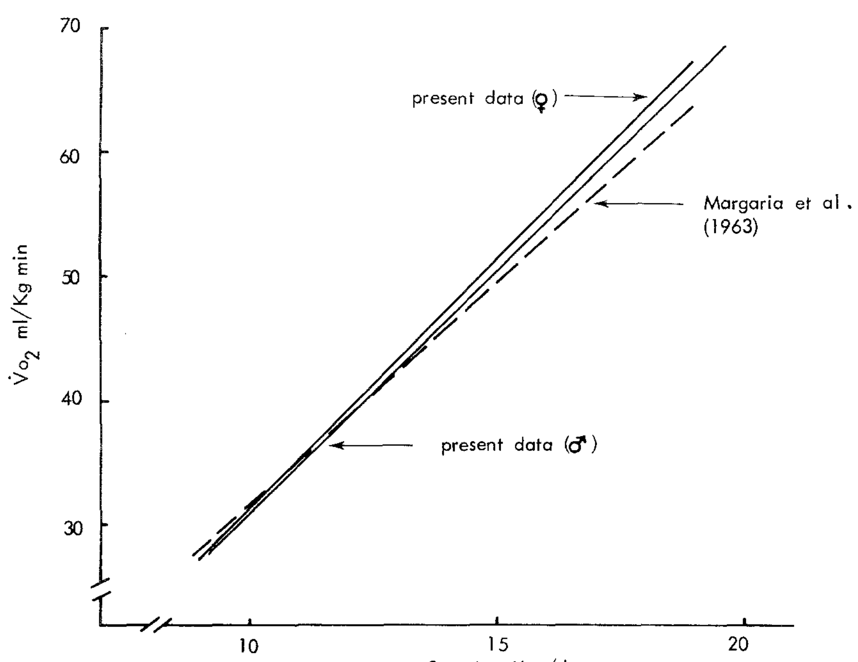

Fig. 1. Oxygen intake ($\dot{V}O_2$) in relation to speed of running at zero gradient on a motor-driven treadmill. Full lines represent the male and female regression lines which are given by: $\dot{V}O_2$ (ml/kg · min) = 8.393 + 3.998 speed (km/h) and $\dot{V}O_2$ (ml/kg · min) = 8.589 + 4.046 speed (km/h), respectively. The dotted line is taken from Margaria et al. (1963)

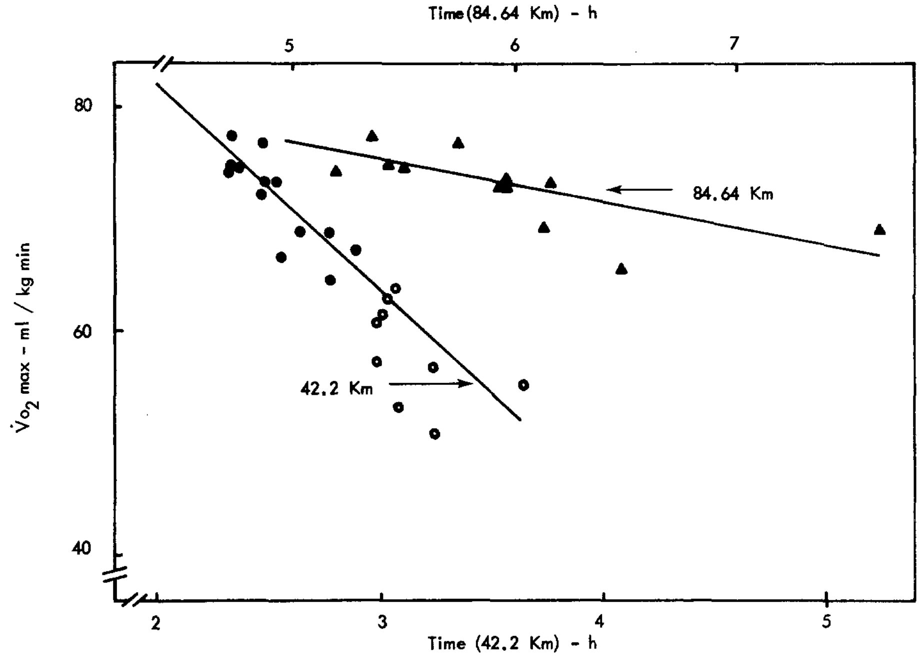

Fig. 2. Maximal aerobic power output ($\dot{V}O_{2\ max}$) in relation to the marathon (42.2 km) and the ultramarathon (84.64 km London–Brighton) times in the male and female athletes. Symbols: 42.2 km (●) males, (○) females. 84.64 km (▲) males. The regression lines are shown for the male athletes and are given by the equations: $\dot{V}O_{2\ max}$ (ml/kg · min) = 117.96 – 18.10. 42.2 km time (h) ($r = -0.82$) and $\dot{V}O_{2\ max}$ (ml/kg · min) = 96.18 – 3.88. 84.64 km time (h) ($r = -0.72$). The regression line for the female athletes at 42.2 km is represented by $\dot{V}O_{2\ max}$ (ml/kg · min) = 87.69 – 9.35. 42.2 km time (h) ($r = -0.43$). The slope of the regression equation is significantly ($p < 0.05$) different from that of the ♂ athletes

performance on the track (Table 2) was given by their 5 km time, $\dot{V}O_{2\ max}$ could be predicted with a standard deviation of ± 2 ml/kg · min using the equation:

$$\dot{V}O_{2\ max}\ (\text{ml/kg} \cdot \text{min}) = 129.73 - 3.617.\ 5\ \text{km time (min)}. \quad (2)$$

Converting the 5 km time to speed (km/h) and using Eq. (1) an equally accurate prediction of $\dot{V}O_{2\ max}$ could be made but the procedure resulted in a systematic underestimation of the observed value of approximately 6% (Table 2). In both the male and female athletes the observed $\dot{V}O_{2\ max}$ was also related to their 42.2 km time (Fig. 2). The relationship was different in the two groups and less strong in the females but in both cases the regression coefficients were statistically significant ($p <$ 0.001). However, the variance in 42.2 km performance times could be further reduced in the ♂ and ♀s by considering the relative work level (%$\dot{V}O_{2\ max}$) they could sustain in the event. On average, the males utilised 82% of their directly observed $\dot{V}O_{2\ max}$ (and sustained a speed equal to 89% of that attained at 5 km – Table 2) compared with 79% in the female athletes (Table 3) but again in both groups the %$\dot{V}O_{2\ max}$ was critically related to performance (Fig. 3). In contrast to the relation-

Table 2. Aerobic and running performance in male athletes from 5 km to 84.64 km. Time, speed, oxygen intake ($\dot{V}O_2$) estimated from Equation 1 (see text) and relative work load (%$\dot{V}O_{2\,max}$)

Athlete	5 km				42.2 km					84.64 km				
	Time (min)	Speed (km/h)	$\dot{V}O_2$ (ml/kg · min)	%$\dot{V}O_{2\,max}$ obs.	Time (h)	Speed (km/h)	%[a]	$\dot{V}O_2$ (ml/kg · min)	%$\dot{V}O_{2\,max}$ obs.	Time (h)	Speed (km/h)	%[a]	$\dot{V}O_2$ (ml/kg · min)	%$\dot{V}O_{2\,max}$ obs.
TK	14.48	20.72	74.4	100.0	2.315	18.23	88.0	64.6	86.8	5.503	15.38	74.2	53.3	71.6
IB	14.88	20.16	72.2	96.7	2.376	17.76	88.0	62.7	83.9	5.442	15.55	77.1	53.9	72.2
JO	15.48	19.38	69.1	93.8	2.495	16.91	87.3	59.3	80.5	6.192	13.67	70.5	46.5	62.2
AJ	17.62	17.03	59.8	90.7	2.888	14.61	85.8	52.2	79.2	6.483	13.06	76.7	44.1	66.9
MWT	16.13	18.59	66.0	90.0	2.469	17.09	91.9	60.0	82.6	5.911	14.32	77.0	49.0	67.5
CW	15.02	19.97	71.5	95.2	2.330	18.11	90.7	64.1	85.4	5.202	16.27	81.5	56.8	75.6
TR	15.67	19.17	68.2	88.5	2.475	17.05	88.9	59.9	77.7	5.753	14.71	76.7	50.6	65.6
TO'R	15.07	19.91	71.2	91.4	2.334	18.08	90.8	64.0	82.2	5.392	15.69	78.8	54.5	70.0
TP	17.07	17.57	61.9	92.9	2.561	16.48	93.8	57.6	86.5	–	–	–	–	–
KW	16.10	18.63	66.2	96.1	2.780	15.18	81.4	52.5	76.2	7.637	11.08	59.5	36.2	52.5
DF	16.50	18.18	64.4	93.0	2.618	16.12	88.7	56.2	81.2	6.139	13.79	75.9	46.9	67.8
AJO	15.90	18.87	67.1	90.9	2.512	16.80	89.0	58.9	79.8	5.950	14.23	75.4	48.7	66.0
DB	15.68	19.13	68.1	96.2	2.472	17.07	89.3	60.0	82.2	5.929	14.28	74.6	48.9	67.0
Mean	15.82	19.02	67.7	93.6	2.510	16.88	88.7	59.4	81.9	5.961	14.34	74.8	49.1	67.1
± SD	±0.89	±1.05	±4.2	±3.2	±0.172	±1.10	±3.0	±4.0	±3.2	±0.646	±1.39	±5.5	±5.5	±5.8

[a] Speed expressed as % of the 5 km value

Table 3. Aerobic and running performance at 42.2 km in female athletes. Time, speed, oxygen intake ($\dot{V}O_2$) and relative work load ($\%\dot{V}O_{2\,max}$)

Athlete	Time	Speed	$\dot{V}O_2$	$\%\dot{V}O_{2\,max}$
LT	3.069	13.75	46.8	73.7
IW	3.237	13.04	44.0	77.8
LW	3.040	13.88	47.3	76.4
CR	2.979	14.16	48.4	85.3
LB	2.954	14.29	48.9	79.8
PD	3.089	13.66	46.4	87.4
RC	3.037	13.90	47.4	73.6
BN	3.242	13.02	43.9	86.4
JD	3.667	11.51	37.9	68.0
Mean	3.146	13.47	45.7	78.7
± SD	±0.219	± 0.85	± 3.4	± 6.6

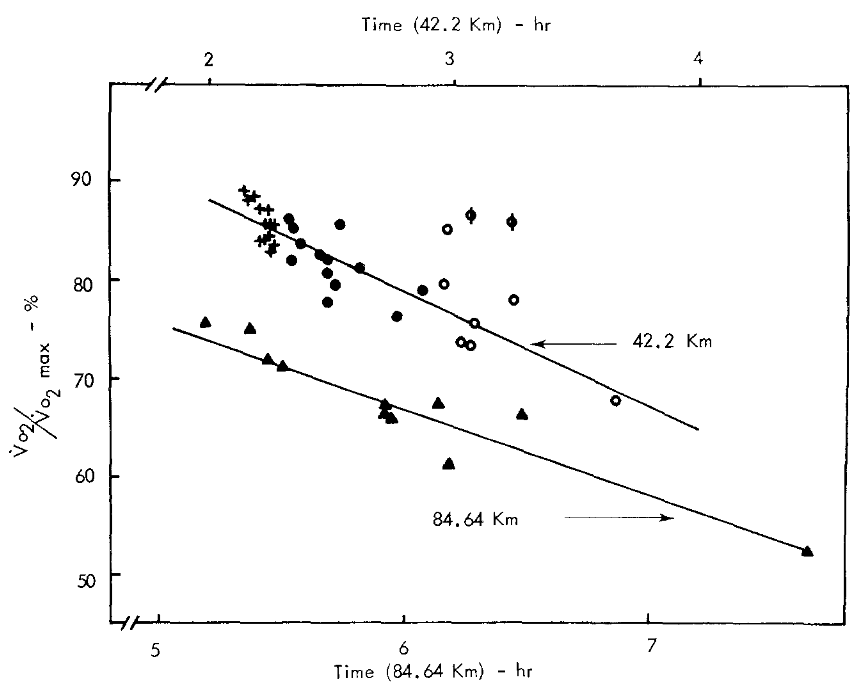

Fig. 3. Relative ($\dot{V}O_{2\,max}$) aerobic energy expenditure in the female marathon (42.2 km) and the male ultramarathon (London to Brighton = 84.64 km) events. The regression (full) lines are given for the males by: $\%\dot{V}O_{2\,max} = 111.52 - 11.82$. 42.2 km time (h) ($r = -0.63$), $\%\dot{V}O_{2\,max} = 116.51 - 8.29$. 84.64 km time (h) ($r = -0.93$). The regression equation for the female athletes at 42.2 km is $\%\dot{V}O_{2\,max} = 125.93 - 14.98$. 42.2 km time (h) ($r = -0.47$) is not statistically different ($p > 0.05$) from the male equation and therefore if one wishes the data may be combined. Symbols: (+) Elite athletes see Table 4; (ϕ) PD and bN see Subjects and Methods and remaining symbols see Fig. 2

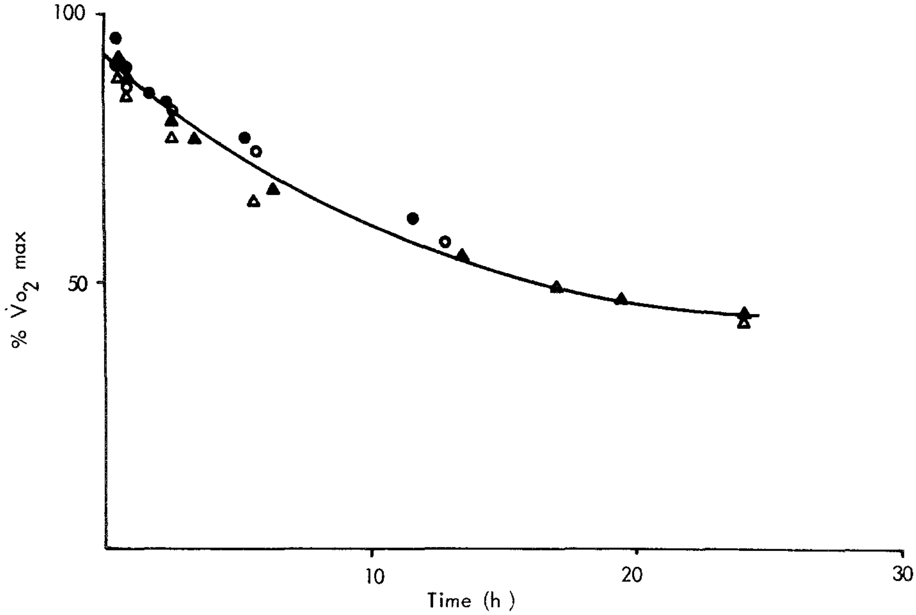

Fig. 4. The relationship of sustainable relative aerobic power output (%$\dot{V}O_{2\ max}$) in relation to time in four elite ultralong-distance athletes. CW (●); TR (△); MWT (○) and DF (▲). The curved line is represented by the equation: %$\dot{V}O_{2\ max}$ = 91.24 − 3.79 time (h) + 0.08 time^2 (h) (r = 0.985)

ship for $\dot{V}O_{2\ max}$ the regression equations of %$\dot{V}O_{2\ max}$ on 42.2 km time could be combined:

$$\%\dot{V}O_{2\ max} = 100.11 - 7.046.\ 42.2 \text{ km time (h)} \ (r = -0.52).$$

At distances beyond the marathon in the male athletes the relationships of aerobic power to running performance were maintained (Figs. 2 and 3) but at 84.64 km importance of the relative work that could be sustained was increased ($r = -0.93$) and had a greater influence on performance time than the absolute $\dot{V}O_{2\ max}$ ($r = -0.72$).

The relationship between time of performance and relative sustainable work level is shown in Figure 4.

Discussion

The results of the present study show that, despite the well defined differences in body size and shape (Table 1) and the recently established (Nelson et al., 1977) biomechanical variation in running techniques between the sexes, the O_2 cost of running on a motor driven treadmill when standardised for body weight is the same in male and female athletes. This observation is at variance with the recent data of Bransford and Howley (1977) who found male athletes to be more economical than trained female runners. Our data clearly shows the relationship of $\dot{V}O_2$ and speed to be linear and to hold across the sexes in treadmill running (Fig. 1). Quadratic and higher polynomial regression equations did not significantly reduce the variance ($p >$ 0.1). Our data agrees closely with Åstrand (1952), Margaria et al. (1963), and many others (e.g., Dill, 1965), though the efficiencies of our runners were less than those reported by Costill et al. (1973) and Pugh (1970). The energy cost in terms of kcal/kg · km for our athletes is 0.95 which is exactly the figure given by Margaria et al. (1963) for the energetics of running. We found no evidence to suggest that performance in the marathon and ultramarathon events was critically dependent on running economy (Costill, 1972). On the contrary, the times for these events were associated with only two major factors the $\dot{V}O_{2\ max}$ and the relative aerobic work level which could be sustained during competition (Fig. 3).

Our $\dot{V}O_{2\ max}$ values for the male athletes (mean 72.5 ml/kg · min; range 65.9–77.9 ml/kg · min) are closely in agreement with those reported for male marathon runners (Costill, 1970; Costill and Fox, 1971) and are 10–12 ml/kg · min less than the figures obtained on elite middle distance runners (Saltin and Åstrand, 1967). However, it is perhaps noteworthy that our athlete DF who was aged 50 years and is the subject of further series of observations concerned with 24 h running (Davies and Thompson, 1979), had a $\dot{V}O_{2\ max}$ of 69.2 ml/kg · min. To our knowledge this is the highest value of aerobic power output reported for a man of his age. It may be compared to Costill's subject Cor's (aged 49 years – 42.2 km time 2.691 h) value of 65.1 ml/kg · min and the famous marathon runner De Mar who had at the age of 49 years a $\dot{V}O_{2\ max}$ of 60 ml/kg · min (Dill, 1965). The women athletes mean $\dot{V}O_{2\ max}$ value (58.2 ± 4.8 ml/kg · min) was approximately 20% below that of their male counterparts and in close agreement with the values for ♀ distance runners recently reported by Wilmore and Brown (1974) – 59.1 ml/kg · min – and Daniels et al. (1977) – 59.6 ml/kg · min. The highest $\dot{V}O_{2\ max}$ value observed on subject RC (aged 25 years, 42.2 km time 3.037 h – Table 1) of 64.4 ml/kg · min in the present study is similar to that reported for elite female cross country skiers (63 ml/kg · min – Saltin and Åstrand, 1967), but is significantly less than the measurement obtained on the world's best female marathon athlete (42.2 km time 2.828 h) of 71.1 ml/kg · min which stands as the highest recorded value of aerobic performance on women to date (Wilmore and Brown, 1974). The directly observed aerobic power outputs in the present study are associated with running performance from 5–84.64 km, but the magnitude of the correlation between the two variables diminishes with increasing distance. From the 5 km times $\dot{V}O_{2\ max}$ may be predicted with a SD of 2 ml/kg · min in the men (Eq. 2) but converting times to speeds and using Eq. 1 reveals that the mean estimated $\dot{V}O_{2\ max}$ is approximately 6% below the observed value (Table 2). However, two important points should be noted, our $\dot{V}O_{2\ max}$ observations were made using a motor driven treadmill, the speed of which was maintained constant and the gradient raised to achieve maximal values. Åstrand and Saltin (1961) has shown that this procedure may give 5% higher values than running on the level. Equally, no account was taken of wind resistance in our experiments. Recently, Pugh (1970) has shown that the O_2 cost of running outdoors against a wind increases as the square function of its velocity. On a calm day the $\dot{V}O_2$ is proportional to the cube of the athletes running speed. On the treadmill, of course, the wind resistance is effectively zero. Thus, over the range of speeds recorded for the 5 km on the track and using a mean projected area for our athletes estimated from the formula given by Pugh (1970) wind resistance could account for ~ 5% of the $\dot{V}O_2$ of running. Either one or both of these factors could account for the lower estimated $\dot{V}O_{2\,max}$ values from 5 km time given in Table 2, though it should be noted that recently McMiken and Daniel (1976) have failed to demonstrate a difference in $\dot{V}O_2$ between track and level treadmill running. It may be that small differences in efficiencies between performance on the track and treadmill compensate for (or possibly obscure) the effects of wind resistance in the two situations. It is certainly of interest that Pugh's track data agrees precisely with our laboratory observations which were obtained on a traditional (modified Collins) 'rollerbed' treadmill and we are currently investigating this problem further. In the meantime we hold the view that the 5 km time provides a useful guide to the endurance athletes $\dot{V}O_{2\,max}$ and provides a worthwhile physiological tool for field studies.

At the longer distances, as stated, the correlation between $\dot{V}O_{2\,max}$ and running performance diminishes, but again in contrast to Costill (1972), who found the two variables to be unrelated ($r = +0.08$), it does remain significant ($p < 0.001$) at both 42.2 km and 84.64 km (Fig. 3). In the male athletes the correlations between $\dot{V}O_{2\,max}$ and 42.2 km and 84.64 km times were −0.82 and −0.72 respectively. In the females at 42.2 km the association was less strong ($r = -0.43$) but nevertheless remained significant ($p < 0.001$). The residual variance in performance in both sexes as distance increased could be accounted for in terms of relative sustainable work output. In the male athletes $\%\dot{V}O_{2\,max}$ was responsible for 36% and 80% of the total variance of 42.2 km and 84.64 km times, respectively. In the women the respective figure for 42.2 km was 25%. Indeed, multiple regression analysis revealed that using the following formulas:

$$42.2\text{ km time (h)} = 7.445 - 0.0338\ \dot{V}O_{2\,max}\ (\text{ml/kg}\cdot\text{min}) - 0.0303\ \%\dot{V}O_{2\,max}\quad (r = 0.993),$$

$$84.64\text{ km time (h)} = 16.998 - 0.0735\ \dot{V}O_{2\,max}\ (\text{ml/kg}\cdot\text{min}) - 0.0844\ \%\dot{V}O_{2\,max}\quad (r = 0.996).$$

Of the variance of performance times 97—98% could be accounted for in the two events. This supports the view that other factors such as running technique, clothing, weight of footwear (Costill, 1972) etc., in a temperate climate and at least for the groups of athletes observed in this study, play a relatively minor role in determining overall performance in marathon and ultralong-distance running.

The relationship between $\%\dot{V}O_{2\,max}$ and performance time in long-distance running found in the present study precludes specific statements regarding the relative work load which can be sustained for a given distance by marathon and ultramarathon athletes and may help to explain the contradictory results which have been reported in the literature. For example, Costill and Fox (1969) and Dill (1965) have suggested that the marathon (42.2 km) is run at 75—77% $\dot{V}O_{2\,max}$, longer distances at 60% $\dot{V}O_{2\,max}$ and yet Costill and Winrow (1970) report that two middle-aged runners could sustain 80—85% $\dot{V}O_{2\,max}$ for 2.5 to 5.5 h. Indeed, their subject, McDough, averaged 83.5% $\dot{V}O_{2\,max}$ for 60.4 km and 78% $\dot{V}O_{2\,max}$ for 84.5 km. Costill et al. (1971) later reported that Clayton (still the holder of the world's best recorded time for the marathon of 2.143 h) was capable of working at 86% $\dot{V}O_{2\ max}$ for prolonged periods. Our data could be used to support all these figures depending on the population of athletics sampled. The present male athletes were capable of maintaining 81–92% and 60–82% of their 5 km running speed for 42.2 and 84.64 km, respectively (Table 2). In terms of O_2 cost this represents 76–87% and 53–76% of their uphill $\dot{V}O_{2\ max}$ values observed in the laboratory. The top marathon runners in the world are probably capable of sustaining even greater relative work outputs during a 42.2 km race (Table 4). Using 5 km time to predict $\dot{V}O_{2\ max}$ (Eq. 2) their $\%\dot{V}O_{2\ max}$ values range from 85–92%. In fact the small differences in relative sustainable work load would appear to be decisive in these athletes, all of whom have a highly developed (and similar) aerobic capacity (Table 4 and Fig. 3). These differences in sustainable $\dot{V}O_{2\ max}$ between the different groups of athletes are undoubtedly in part due to training, but they may also reflect experience. For instance, it will be seen from Table 3 that the women operate at lower $\%\dot{V}O_{2\ max}$ (mean 79% range 68–87%) in the marathon than the men and, indeed, the physiological performance of the female athletes at 42.2 km is closely similar to the men in the longer (London to Brighton) ultramarathon event (Tables 2 and 3 and Fig. 3). In both cases the performance may be explained partly in terms of experience and the prolonged training required to achieve and sustain an aerobic power output close to maximum. It is noteworthy that the two older (and more experienced) female runners (PD and BN, Table 1) were able to sustain approximately 87% of their $\dot{V}O_{2\ max}$ during the marathon (values comparable with the elite male athletes) and thereby compensate for the effects of advancing age on $\dot{V}O_{2\ max}$ (Robinson, 1938; Åstrand, 1960), whereas subject JD, a newcomer to marathon running could only achieve 68% $\dot{V}O_{2\ max}$ (Table 1). Similarly the elite male ultra long distance athlete (CW) achieved approximately 76% $\dot{V}O_{2\ max}$ compared with the 53% $\dot{V}O_{2\ max}$ in KW who was competing in the London to Brighton race for the first time. The marathon is a comparatively new sport for females and in general the male athletes tend to progress to ultramarathon running from the comparatively shorter (16–42 km) events as their athletic career advances. The intersubject differences in sustainable $\% VPO_{2\ max}$ can in part be removed by considering time of performance rather than distance (Fig. 4). The relationship between $\%\dot{V}O_{2\ max}$ and time is described by a quadratic equation of the form:

$$\%\dot{V}O_{2\ max} = 91.24 - 3.79 \text{ time (h)} + 0.08 \text{ time}^2 \text{ (h)}.$$

The curve suggests that elite ultralong-distance runners can sustain 87.5 $\%\dot{V}O_{2\ max}$ for 1 h 66.0% for 8 h and 46.4% over a full day and night (24 h) period. These figures should be compared with the data of Costill and Fox (1969) and Åstrand (1960) for trained and untrained subjects, respectively, working for periods up to 8 h and with the statistical predictions of Khosla (1974). The latter author on the basis of early figures concluded that three times the traditional marathon distance could be run non-stop at a speed not exceeding 3 m/s 10.8 km (h) in a time of 11.72 h by some future champion. Five athletes in the present study, DF (11.64 km/h), TR (11.83 km/h), MWT (12.66 km/h), TOR (13.36 km/h), and CW (13.82 km/h) have achieved average speeds well in excess of Khosla's prediction over greater periods of time and distance. Indeed, TR averaged 10.48 km/h (which corresponded to an

Table 4. Running and estimated aerobic performance of the elite male British marathon athletes. Estimated maximal aerobic power output ($\dot{V}O_{2\,max}$ – from Eq. 1 in text). 5 km time, speed, estimated oxygen intake ($\dot{V}O_2$ from Eq. 2 in text) and relative work load ($\%\dot{V}O_{2\,max}$)

Athlete	Estimated $\dot{V}O_{2\,max}$ (ml/kg · min)	5 km				42.2 km				
		Time (min)	Speed (km/h)	$\dot{V}O_2$ (ml/kg · min)	$\%\dot{V}O_{2\,max}$	Time (h)	Speed (km/h)	%[a]	$\dot{V}O_2$ (ml/kg · min)	$\%\dot{V}O_{2\,max}$
Thompson	78.8	14.09	21.29	76.7	97.3	2.153	19.60	92.1	70.0	88.8
Hill	79.3	13.94	21.52	77.6	97.9	2.158	19.56	90.9	69.8	88.0
Adcocks	78.2	14.25	21.06	75.8	96.9	2.180	19.36	91.9	69.0	88.2
Alder	78.2	14.24	21.36	77.0	98.5	2.201	19.17	89.8	68.3	87.3
Faircloth	78.2	14.26	21.04	75.7	96.8	2.205	19.14	91.0	68.2	87.2
Stewart	80.4	13.64	21.99	79.5	98.9	2.220	19.00	86.4	67.6	84.1
Wright	80.4	13.65	21.97	79.4	98.7	2.224	18.97	86.4	67.5	84.0
Heatley	79.6	13.85	21.66	78.2	98.2	2.232	18.91	87.3	67.2	84.4
MacGregor	78.5	14.15	21.20	76.3	97.2	2.238	18.86	88.9	67.1	85.5
Plain	80.4	13.64	21.99	79.5	98.8	2.249	18.76	85.3	66.7	83.0
Watson	77.9	14.33	20.93	75.3	96.7	2.252	18.74	89.5	66.6	85.5
Kirkham	77.5	14.45	20.76	74.6	96.3	2.255	18.71	90.1	66.5	85.8
Angus	79.3	13.93	21.53	77.6	97.8	2.265	18.63	86.5	66.1	83.4
Mean	79.0	14.03	21.41	75.0	97.7	2.218	19.03	88.9	67.7	85.8
± SD	±1.0	±0.27	±0.41	±1.0	±0.9	±0.037	±2.32	±2.3	±1.3	±2.0

[a] 42.2 km speed expressed as % of 5 km value

estimated 47% of his $\dot{V}O_{2\,max}$ – Davies and Thompson, 1979) when covering non-stop a distance of 251.5 km over a period of 24 h.

Finally, Pugh et al. (1967) have suggested that a 2 h 10 min run requires a $\dot{V}O_2$ of 61 ml/kg · min. Our data would suggest the figure is nearer 70 ml/kg · min and that modern marathon runners require a $\dot{V}O_{2\,max}$ approaching 80 ml/kg · min to excel at their chosen sport. It is of some interest and surprise that Costill et al. (1971) report that Clayton's $\dot{V}O_{2\,max}$ is 69.7 ml/kg · min which from our data would require him to operate at this value to achieve his world best time at 42.2 km. Costill and his co-workers suggest that Clayton's efficient running style compensated for his relatively "low" $\dot{V}O_{2\,max}$. We cannot comment on this finding directly except to say that though we did find intersubject variation in efficiency (of the order of 5%) this factor was not reflected in their performance time. We have found that the ability to succeed at marathon and ultralong-distance running is almost wholly dependent on a well developed aerobic power output and the capacity to utilise and sustain a given relative work output during competition. This probably explains why individual performances for a specific event are so hazardous to predict in the marathon. For a group of elite athletes, all of whom have a well (and similarly) developed $\dot{V}O_{2\,max}$, the differences in performance will rest on the ability to utilise and sustain their aerobic capacity within very narrow limits (Table 4). This may depend on the day of the race on psychological as well as physiological factors.

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