how elderly people spend their daily lives and how energetic a life they may be capable of leading before we can adequately discuss this whole question.

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Energy expenditure in athletic activities

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Textbooks on the physiology of muscular activity now contain so much information on the energy expenditure during athletic activities (e.g. that of Karpovich, 1953) that anyone interested may read them with profit. On the present occasion, therefore, I shall deal rather cursorily with recorded results of a few activities and dwell rather on incidental points of interest. First let us look at a few general points.

The practical and theoretical difficulties of estimation of energy output based on measurement of respiratory exchange are well known to all who have seriously considered the problems. Apart from the convenience of having results in calories for comparison with those of dietary surveys, one might, for most purposes, use figures for oxygen consumption. These are liable mainly to practical, not so much to theoretical, errors of determination and interpretation.

And one ought always to consider whether the real cost, over and above that for maintaining the resting state, is required, or whether the current energy expenditure is sufficiently accurate. This point is a source of great confusion in the literature. Comparatively few authors have measured the oxygen debt (or postulated none) and most have thus been unable to calculate the total as distinct from the current cost of the activity. Probably a good deal of the real variation between individual performers is thereby lost.

Many estimations have, for the purpose of convenience in recording or for accurate control of speed, been made using treadmills or ergometers in the laboratory; yet almost no results have been published validating the transfer of results to out-of-doors activities. Campbell (1924) found that the O_2 uptake for one subject running on the road and on a treadmill was about identical (Table 1), which would validate generalizing. I have found that the O_2 uptakes were not significantly different for a trained runner at a speed of $7\frac{1}{2}$ m.p.h. on the cinder track and on a treadmill

Table 1. *Oxygen uptake by a subject running on the track and on a treadmill*
(Each author used one subject)

Reference	Speed (m.p.h.)	Time (min)	Time of collection of expired air	O$_2$ uptake (l./min) Track	O$_2$ uptake (l./min) Treadmill
Campbell (1924)	8·9	1·7	Last 55 sec	2·50	2·40
	5·8	7·5	3·7 min	1·81	1·84
Noltie (unpublished)	7·5	24	6 × 2 min	2·39 ± 0·03*	2·20 ± 0·02†

* Mean value for six experiments with its standard error.
† Mean value for ten experiments with its standard error.

even though the track runs were spread over two summers and there was considerable scatter of values.

Values recorded in the literature

As only to be expected, most measurements of energy expenditure during violent activity (which covers most athletic activity) have been made on subjects exercising in the laboratory. Here adequate incentives to maximum effort can rarely exist, yet some very high rates of energy output have been put up by skilled subjects. Until recently almost no direct measurements had been made of the energy expended in playing competitive games and even now for no characteristically team games such as football—for obvious reasons.

In this paper only the results of a few authors for a few activities have been arbitrarily selected as being fairly typical, or else as the only ones a cursory search disclosed.

Walking. Walking economically is at all times a skilled activity, and fast walking is certainly an athletic activity. I shall direct attention to only two of the numerous
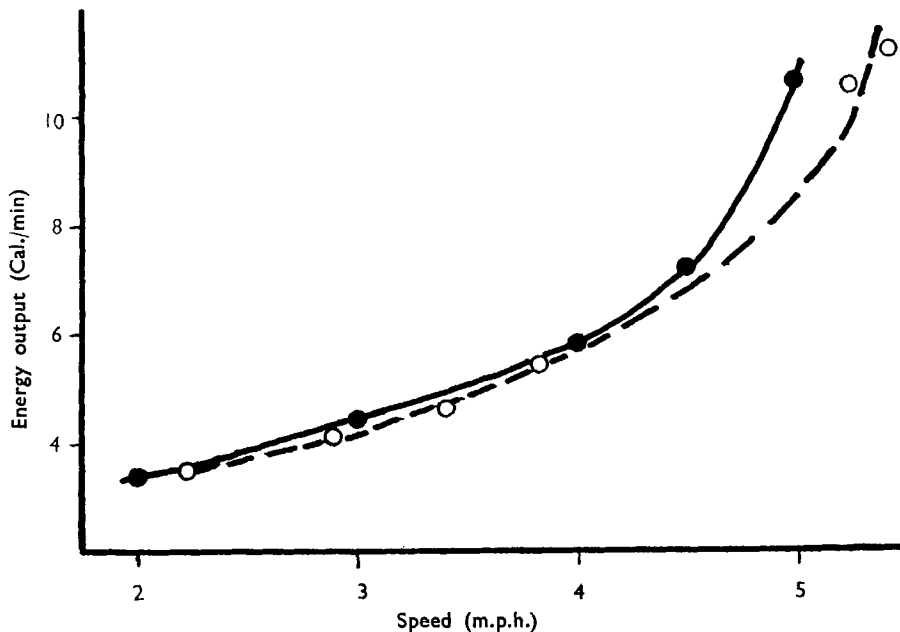

Fig. 1. Energy output by one subject walking at different speeds. ●, round laboratory (Douglas & Haldane, 1912); ○, on treadmill (Benedict & Murschhauser, 1915).

sets of figures available; firstly the oft quoted early experiments of Douglas & Haldane (1912), where the current expenditure for a subject walking round a large room was at the rate of 3·4 Cal./min for a speed of 2 m.p.h. and 10 Cal./min for 5 m.p.h. (Fig. 1.) The same subject walking backwards and forwards on grass expended somewhat more energy; not surprising perhaps as the beat was only 50 yd. long. Secondly we might consider the results of Benedict & Murschhauser (1915) also for a single subject, but on the treadmill. Their figures, though a little less, are of the same order of magnitude. Both curves tend to steepen rather rapidly after 4½ m.p.h. Most people are aware that it is often easier to run slowly than to walk fast.

Running. The bulk of available results is for runners, occasionally expert, on the treadmill. Some figures for a good middle-distance runner (Christensen & Högberg, 1950a) show (Table 2) how high he could lift his O_2 uptake and also, if

Table 2. *Oxygen uptake by subject P.H., weight 74·5 kg, running at different speeds on a treadmill*

(Values taken from a graph of Christensen & Högberg, 1950a)

Speed		O_2 uptake
km/h	m.p.h.	(l./min)
10	6·2	2·50
12	7·4	2·89
14	8·7	3·58
16	9·9	4·00
18	11·2	4·50
20	12·4	4·88

we assume a reasonable calorie factor, his energy output at various speeds up to 20 km/h (12·4 m.p.h.). The figures can be regarded as representative of skilled runners for non-sprint speeds.

We have figures for more ordinary, though experienced, runners on Leeds University cinder track (Table 3). When they were in the steady state, running at

Table 3. *Extra oxygen uptake and extra energy output by Leeds University runners on a cinder track*

(Mean values for steady-state laps (resting O_2 deducted) in from four to fourteen experiments on each subject running at different speeds in different seasons (Noltie, unpublished))

Speed (m.p.h.)	Subject	Weight (kg)	Extra O_2 uptake (l./min)	Extra energy output	
				Cal./min	Cal./kg/min
10	N.	70	3·27	16·2	0·231
	L.	73	3·49	17·6	0·241
	E.	67	2·96	14·9	0·223
8½	N.	70	3·33	16·8	0·240
	D.	70	3·26	16·4	0·234
7½	N.	70	2·48	12·0	0·172
	F.	62	2·66	12·9	0·208
	M.	78	3·34	16·1	0·206

10 m.p.h., their net-energy output averaged 0·23 Cal./kg/min, compared with the Scandinavian gross figure of about 0·27 for about the same speed on the treadmill. On the basis of our figures an experienced runner, in fair condition, would, on the track, spend energy at the rate of about 16 Cal./min for a speed of 10 m.p.h., almost the same at 8½ m.p.h. and about 13 Cal./min at 7½ m.p.h.

Effect of alteration of style of walking or running. As can readily be imagined there is an easiest length and also frequency of stride for any given speed of walking or running. The point at which a runner will quicken rather than lengthen his stride so as to gain speed is very much an individual characteristic. One knows by observation that the shorter-legged runner tends to keep a longer stride than the tall man when running fast.

Figures given by Högberg (1952) (Table 4) for a good middle-distance runner show that both parameters matter when determining the most economical style of

Table 4. *Optimal striding in running, and oxygen uptake, of a trained runner on a treadmill*

(Mean values for from four to six experiments (Högberg, 1952))

Speed				
km/h	m.p.h.	Optimum strides/min	Stride length (cm)	O₂ uptake (l./min)
14	8·7	173	119 (shortest)	3·55
			135 (optimal)	3·35
			153 (longest)	3·75
16	9·9	179	135 (shortest)	4·03
			149 (optimal)	3·87
			169 (longest)	4·52

The differences in oxygen uptake are significant.

running. The style adopted will affect very much the upward and downward bouncing of the body and hence the work done against gravity.

The figures produced by Benedict & Murschhauser (1915) (Table 5) for their subject on the treadmill show how the increased frequency of striding on changing from walking to running adds to the lifting of the body. But the energy expended is less for running than for walking at the same speed when the walking is fast, so the extra lift of the centre of gravity cannot be very costly and is completely masked by the cost of the very vigorous propulsive action of the arms and shoulder muscles

Table 5. *Mechanics of walking and running studied with a professional cyclist on a treadmill*

(Benedict & Murschhauser, 1915)

Activity	Speed (m.p.h.)	Mean no. of steps/min	Mean step length (in.)	Raising of the body		
				Per step (in.)	Per min ft.	in.
Slow walk	2·58	108	25	1·05	9	5½
Fast walk	5·38	152	37	2·04	25	11
Slow run	5·50	182	32	2·97	45	0

necessary to maintain fast striding in walking. In running the subject tends to lean forward more than in walking which would assist the forward progression.

The fallacy of the fast start. Consideration of the relative efficiencies of aerobic and anaerobic workings shows immediately that a fast start to any activity, notably competitive running, without previous limbering up may be too costly to permit finishing the task, let alone putting up a good performance.

In recent times a number of authors have drawn attention to what was actually pointed out quite a time ago, namely that anaerobic work is performed at only a fraction of the efficiency of aerobic. Thus a relatively large O_2 debt is built up at the start of violent activity before the machine has reached top gear. In sustained violent exercise such a debt is unlikely to be paid off during the activity, and, since only a fixed maximum debt can be borne by the individual, the total duration must be affected or else the pace must slacken. Christensen & Högberg (1950*c*) in discussing this point have a very interesting graph (their Fig. 1), showing for one skilled runner on a treadmill set at 20 km/h (12·4 m.p.h.) how costly the initial anaerobic phase is. His first 15 sec was at an O_2 cost of 13 l./min, compared to a later steady-state cost of some 6–7 l./min.

Thus a wild anaerobic rush at any time during a race may almost immediately bring the runner across the red line for current expenditure. The physiologically soundest policy is thus to strike the highest sustainable average pace and maintain it up to the last possible moment; after that psychology matters fully as much as physiology, and recovery can come after the tape has been breasted. But theory and practice do not always agree when it comes to competitive running; for a race may be won by tactics which could not possibly produce a good time. And one should remember that modern methods of overload training have made the O_2 uptake and the bearable limit of O_2 debt remarkably high for world-class athletes. Any old runner must have felt his hair rising if he was watching the Chataway-Kuts duel in London last year.

The corollary—the value of steady lapping—is well illustrated by a study of the lap times for the A.A.A. 3 miles' championship of 1954. In the first lap Maiyoro averaged 7·19 yd./sec but by the seventh had fallen to 6·13 and in the last could do only 5·95. The leaders, Green and Chataway, in their first lap did 6·99, at no time fell below 6·23 (penultimate lap) and were rarely more than a fraction below their average of 6·50 yd./sec.

Swimming. Because of the much greater resistance of water, swimming is a more costly means of progression. Amongst earlier investigators Liljestrand has furnished results for free swimming (Liljestrand & Stenström, 1920*a*), but only at slower speeds up to $1\frac{1}{2}$ m.p.h. Karpovich's results (which I have read from his graphs) (Karpovich & Millman, 1944) are for faster speeds by swimmers skilled at each style. They swam for only a length or so in the bath and held their breath the while so that their computed energy output is the real cost. As Karpovich remarks in his textbook, the appropriate style should be chosen for any desired speed of swimming. The butterfly is the most costly under speeds of $2\frac{1}{2}$ ft./sec (*c.* 2 m.p.h.); above this it is more economical than the side stroke. Over 3 ft./sec it is more economical

of energy than the breast stroke but tends to be rather fatiguing as so violent use is made of the shoulder-girdle muscles. The largest expenditure he found, namely nearly 150 Cal./min for swimming back stroke at 5·2 ft./sec ($3\frac{1}{2}$ m.p.h.) for a very short time, is just a little above that for Fenn's (1930) sprinter.

Ski-ing. A number of papers are available in the literature, but the highest O_2 consumption is by the skilled skier observed by Christensen & Högberg (1950b). For a speed of 9 m.p.h. on loose snow on a quiet, cold day his O_2 uptake rose to $5\frac{1}{4}$ l./min, so his energy output was over 26 Cal./min, despite carrying a frame for the Douglas bag. None of the other subjects then measured, nor those of Liljestrand & Stenström (1920b) came near this rate of output. Ski-ing is obviously a very strenuous exercise when done at speed, as Christensen gives O_2 uptakes of 58, 63, 67 and 69 ml./kg/min for men, with 58 and 64 for women. The second woman, weighing 58 kg, during maximum speed on the level, reached an O_2 uptake of 3·74 l./min.

As a matter of interest one might now refer to Robinson's (1938) figures of large O_2 uptakes; but they include that of only one young athlete of world class, Lash. To them one can now add many more, e.g. for Christensen's skier and for Bannister running to exhaustion on an inclined treadmill, 65·8 ml./kg/min (Bannister, Cunningham & Douglas, 1954).

Rowing. From the nature of the activity and the number of muscles involved in a complete stroke, one would expect to find very large outputs of energy during competitive rowing. Liljestrand & Lindhard (1920) gave figures for three individuals rowing at slow speeds for a few minutes; getting up to 11 Cal./min for a speed of 3·6 m.p.h. They noted the large variation between individuals.

Henderson & Haggard (1925) tested, on a specially devised rowing machine, five of the Yale crew who won their 1924 Olympic race, and measured the recovery O_2 as well as the uptake so as to get the total energy expenditure. For a stroke rate of about 30 the energy cost was about 20 Cal./min, measured for the steady state during a 5 min spell. One rower on repeating at a rate of 40 put his current expenditure up to almost 30 Cal./min. It was estimated that for their Olympic race the crew averaged $\frac{1}{2}$ h.p. for the 22 min they took to row the 4 miles.

Some other athletic activities. Estimation of the energy output during the playing of team games is almost impossible unless the players perform very much as isolated individuals. Some recent figures for cricket are available (Edholm, Fletcher, Widdowson & McCance, 1955) and the energy expenditure for several individualistic games is given in the M.R.C. special report on the energy expenditure by East Fife miners (Garry, Passmore, Warnock & Durnin, 1955).

The respiration chamber has on occasion been utilized to measure the energy expenditure in athletic activities which were not too space-consuming. Two Finnish investigators, Gullichsen & Soisalon-Soininen (1921) have published figures for fencing and wrestling. For the former an average figure of 9–10 Cal./min was found and for the latter 16 Cal./min. But obviously the figures would depend very much on whether the contestants had met before and on whether there was anything at stake; a live competition would no doubt increase the energy output considerably.

In conclusion, the energy expenditure in athletic activities seems to range from

the extraordinarily high figure of 150 Cal./min for 'sprint-like' activities lasting 20 sec or less to one-fifth of that output for 'endurance' activities lasting up to half an hour. But measurements have only occasionally been made outside laboratory conditions and few are available for present day athletes of the 'world class' so the figures recorded in the literature are to be regarded as only first approximations.

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