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ENERGY EXPENDITURE DURING STEPPING

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Previous studies from this department have emphasized the wide variations occurring amongst healthy young adults, both in the daily intake of energy as judged by records of food consumption, and in energy expenditure recorded by indirect calorimetry, for a set task such as walking under standard conditions (Kitchin and others, 1949; Delbue and others, 1949). Although no correlation was demonstrated between energy intake or food consumption and energy expenditure, the suggestion was put forward that these variations might reflect widespread differences in internal economy or individual muscular efficiency, and the possibility was mooted that some " can go more miles to the gallon " than others. Since walking is such a complicated muscular movement and involves no readily measurable performance of external work, it is not well suited for a study of variations in muscular efficiency. Two classical techniques have been used for this purpose, involving the use of either a stationary bicycle ergometer or a power-driven treadmill with variable gradient. These machines have provided valuable information concerning energy expenditure, but each suffers from an important drawback. With the bicycle ergometer, there is the effect of practice and training on the efficiency with which the special movements involved in stationary bicycling are carried out; with the treadmill the initial cost is very high. A study of energy expenditure involved in performing the work necessary to lift the bodyweight up and down on to a series of stools of graded heights offers an alternative technique for assessing variations in muscle efficiency. It is well known that efficiency varies with the speed of movement. Accordingly, a series of observations have been made stepping at different speeds on to stools at different heights. The effects of stepping on to stools of standard size upon the cardio-respiratory system have already been widely used as tests of physical fitness, and are the basis of the Harvard step test (Brouha and others, 1944).

METHODS

Energy utilization was determined by indirect calorimetry using the Douglas bags and Haldane gas-analysis apparatus (Douglas and Priestley, 1948). Three stools, 5, 10, and 20 in. (12·7, 25·4, and 50·8 cm.) in height, were used and the standard task was raising and lowering the body 30 ft (9·14 m.)—the higher the stool the fewer the necessary steps. Measurements of oxygen usage were recorded when the time taken over this work varied from 30 to 270 seconds. Oxygen consumption was always measured over 8 minutes, allowing a period for recovery of oxygen debt incurred during the performance of the work, varying from $7\frac{1}{2}$ minutes for rapid work to $3\frac{1}{2}$ minutes with very slow working rates. At rapid rates, the debt was found to be 80 per cent. of the total oxygen expenditure but only 20 per cent. at the lowest rates. Oxygen consumption, when standing at ease, was determined at the beginning and end of each set of observations; these nearly always showed good agreement and, on the few occasions when they did not, the day's results were discarded. Each set of observations was recorded at least 90 minutes after a light meal and after 30 minutes of rest in a chair. In the hope that these observations may prove the basis for investigation in the field, the subjects were not in a fasting state.

Results are expressed as litres of oxygen used, in excess of the standing value, to raise 70 kg. of bodyweight 30 ft. If the R.Q. of this excess respiration is taken to be 0·85 (as it was shown to be in some experiments) and since no external work is performed in stepping down, then the consumption of two litres of oxygen in raising 70 kg. to a height of 30 ft is equivalent to an efficiency of approximately 15 per cent.

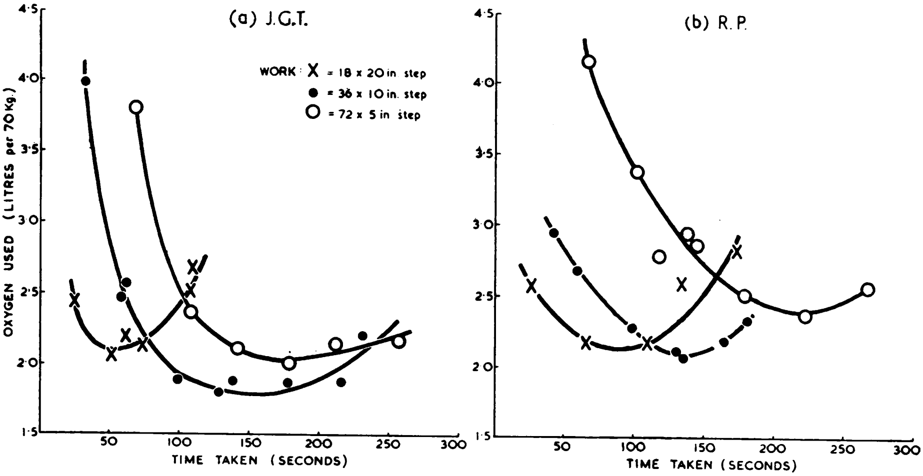

FIGURE.—Oxygen used during stepping up and down 30ft., in excess of basic standing values.

RESULTS

These are shown in the Table (overleaf) and plotted in the Figure (above). Three subjects of different physique were investigated, and in each a minimum oxygen consumption was recorded when stepping on to a 10-in. stool and completing the work in 120 to 160 seconds (about 14 to 18 steps per minute). The minimum rates of utilization of O_2, using the higher and lower stools, were only slightly higher than that for the 10-in. stool. Accordingly, tests with fine gradations of height were not considered necessary. The maximum efficiency of stepping appears to exhibit a broad optimum at a rate of 14 to 18 steps per minute on to a 10-in. stool. The findings are a confirmation and an extension of the work of Lupton (1923), which has found a place in many standard textbooks. Lupton measured the oxygen used in climbing a flight of

78 stairs, with a total height of 12·0 m. He found a minimum oxygen usage when this work was done in just under 100 seconds or 1·3 seconds per step.

TABLE

OXYGEN CONSUMPTION AT DIFFERENT SPEEDS OF STEPPING

Subject	Test	Results									
J.G.T. age 40 yrs. wt. 86 kg. ht. 180 cm.	72 × 5 in.	Time taken (seconds)	72	108	144	180	216	257			
		Excess O_2 1/70 kg.	3·84	2·38	2·12	2·02	2·16	2·18			
	36 × 10 in.	Time taken (seconds)	36	63	63	102	130	140	180	220	234
		Excess O_2 1/70 kg.	4·00	2·57	2·47	1·90	1·82	1·94	1·85	1·86	2·22
	18 × 20 in.	Time taken (seconds)	29	54	64	77	108	114			
		Excess O_2 1/70 kg.	2·46	2·07	2·22	2·17	2·53	2·68			
R.P. age 40 yrs. wt. 63·5 kg. ht. 182 cm.	72 × 5 in.	Time taken (seconds)	69	105	121	140	144	182	225	270	
		Excess O_2 1/70 kg.	4·15	3·38	2·77	2·96	2·88	2·53	2·38	2·57	
	36 × 10 in.	Time taken (seconds)	46	62	100	118	136	138	168	182	
		Excess O_2 1/70 kg.	2·97	2·65	2·29	2·31	2·10	2·14	2·26	2·39	
	18 × 20 in.	Time taken (seconds)	32	69	110	135	176				
		Excess O_2 1/70 kg.	2·57	2·20	2·21	2·62	2·84				
G.P. age 12 yrs. wt. 35·5 kg. ht. 151 cm.	72 × 5 in.	Time taken (seconds)	158	188	240						
		Excess O_2 1/70 kg.	2·43	2·35	2·26						
	36 × 10 in.	Time taken (seconds)	104	120	130	130	160	160			
		Excess O_2 1/70 kg.	2·03	2·12	2·29	2·35	2·22	2·26			
	24 × 15 in.	Time taken (seconds)	52	84	104	120					
		Excess O_2 1/70 kg.	2·52	2·27	2·52	2·59					

On theoretical grounds, Hill (1922) has shown that the efficiency (E) of a muscular contraction is related to the duration of contraction (x) according to the formula

$$E = \frac{0 \cdot 4 \ (1 - \frac{k}{x})}{1 + bx}$$

For flexion at the elbow, using the biceps and brachialis anticus, Hill found $k = 0 \cdot 24$ and $b = 0 \cdot 2$. Our results for a much more complicated group of muscular movements show a loss of efficiency at higher speeds of work similar to that found by Hill. This loss of efficiency is presumed to be due to the increased internal resistance of muscle when contracting at high speeds. Our observations and Lupton's both agree with Hill's formula in demonstrating that the maximum on the curves is very " blunt " and over a wide range of speeds efficiency remains more or less constant. The efficiency at the lower speeds falls off more quickly than predicted by the formula and this is marked when stepping on the high stool. This is undoubtedly due to the extra energy necessary to maintain the posture and balance of the body, during the prolonged slow movement.

The general bearing of these results on industrial life is already well known to physiologists. The demonstration that stepping is a muscular movement with a very broad optimum of efficiency both as regards rate of stepping and height of step, suggests its suitability as a test exercise for the investigation of variation in individual muscular efficiency. Preliminary observations which we have made confirm this.

Summary

The efficiency of stepping over a wide range of rates on to stools of varying heights has been investigated. A broad maximum was found at rates from 14 to 18 steps per minute on to a 10-in. stool (25·4 cm.). This exercise is suggested as a suitable test for measuring individual muscular efficiency and its variations.

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