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BREATHING IN MAN DURING STEADY-STATE EXERCISE ON THE BICYCLE AT TWO PEDALLING FREQUENCIES, AND DURING TREADMILL WALKING

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SUMMARY

1. The breathing pattern, that is the changes in tidal volume (V_T), and in inspiratory (T_I) and expiratory (T_E) durations, has been studied as ventilation increases in exercise.

2. Five healthy subjects were studied in steady-state exercise on a bicycle ergometer, breathing air, at two speeds of pedalling and at six different loads. The pattern was recorded for single breaths. Two of the subjects were also studied while walking on a treadmill with four combinations of speed and gradient.

3. In bicycle exercise, as the CO_2 output increased mean V_T increased, and mean T_I and T_E decreased, the absolute decrease in T_I being small. The pedalling speed did not affect these relationships.

4. Individual breath durations showed no tendency to group around multiples of the period of rotation of the pedals.

5. In treadmill exercise, no clear influence of stride rate on respiratory rate could be found. The pattern was similar to that found in bicycle exercise. Again no grouping could be found.

6. No evidence of an effect of frequency of limb movement on breathing pattern in submaximal exercise has been found. The selection of breathing pattern seems to be unrelated to the nature of the stimulus but closely geared to the metabolic needs of the body.

INTRODUCTION

Interpretation of results obtained during studies of the pattern of breathing in dynamic exercise in man may be complicated by phasic impulses from the working limbs affecting breathing. It has been suggested

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that respiratory frequency, in human exercise, is dependent on movement frequency, perhaps even being a simple submultiple of the latter (Bannister, Cunningham & Douglas, 1954; Asmussen, 1965; Hey, Lloyd, Cunningham, Jukes & Bolton, 1966; Åstrand & Rodahl, 1970). Few data, however, support this statement.

In describing the breathing pattern during exercise it is important to know whether different types of exercise and different frequencies of pedalling on a bicycle produce different relationships between tidal volume and respiratory frequency, or if a unique pattern of breathing exists.

The aim of the present study has been to investigate the pattern of breathing during bicycle exercise at two pedalling frequencies in order to see if any differences were observable, and if respiratory frequency was a submultiple of the movement frequency. Some experiments were also performed on the treadmill to compare the pattern of breathing in two different types of exercise.

A preliminary report on part of this work has been published (Kay, Petersen & Vejby-Christensen, 1974).

METHODS

Five healthy male subjects (18–22 years old) were studied. They were all students, three doing medicine, one physics and one biochemistry. Three (409, 438 and 439) trained regularly for university sport (football, cycling and rowing) whilst the remaining two (454 and 445) took no regular physical exercise. None of them was told the precise purpose of the study. In instructing the subjects before the experiments emphasis was laid on the metabolic aspects during different types and intensities of work.

Each subject was studied from three to five times in the laboratory. Each experimental session lasted approximately 3 hr.

Breathing apparatus. Open-circuit spirometry was used. The subjects breathed through a low resistance, low dead space (50 ml.) modified Lloyd valve. They inspired warm humidified air, and expired through a condenser and a dry gas meter (CD 4, Parkinson & Cowan Ltd, London; this served as a quick guide-line for the experimenter about the level of ventilation) into a wedge spirometer (Oxford Instruments, Oxford) which was emptied during the following inspiration (cf. Cunningham, Lloyd, Miller, Spurr & Young, 1965). Tidal volume (V_T) was determined by integration of the output from the strain gauge in the wedge spirometer. Testing with a sinusoidal pump the output of the wedge spirometer has been found linear in the range of flow rates from 30–300 l. min^{-1}. The durations of inspiration (T_I), expiration (T_E) and the total breath duration (T_T) were determined from the changes in mouth pressure as measured by a sensitive manometer (MDC 301, Hilger - I.R.D. Ltd, London). The respiratory variables were recorded by a multi-channel hot-stylus recorder (M8, Devices Ltd, Welwyn Garden City, Herts) (V_T: 1 l. = 20 mm; T_I, T_T, T_E: 1 sec = 10 mm). Rectal temperature was measured with a thermocouple placed at a depth of 12 cm from the anus and a thermometer(TE 5, Ellab, Copenhagen). Heart rate was measured from the electrocardiogram using precordial leads.

Bicycle exercise. At each of six work loads (50, 80, 110, 140, 170 and 200 W) on a bicycle ergometer (Ergotest, Jaeger, Würzburg) work was performed for 6 min at

50 rev/min followed by 6 min at 70 rev/min. The subjects rested for 30 min and then worked at the same load but with the pedalling frequencies presented in the reverse order. The different work loads were presented in random order; two loads were presented on each day. The subjects maintained a constant pedalling rate by keeping a speedometer needle on a fixed point. The actual speed which this represented was controlled by the gain of an amplifier. In subject 439 only the three lowest work loads were studied, since he could not work for 12 min at the highest loads. Technical faults prevented subject 445 from completing the second 12-min period at 170 W.

In the last minute of each 6-min run a sample of mixed expired air was collected for analysis in the Lloyd–Haldane apparatus (Lloyd, 1958).

Treadmill walking. Subjects 409 and 454 were also studied on the treadmill on a separate day. The experimental session consisted of four periods of exercise each of 6 min, separated by 30 min rest. Periods I and II had the same gradient (7 %), and the speed was 5·3 and 7·0 km/hr respectively. Periods III and IV had the same speed (6·0 km/hr), and the gradient was 4 and 11 % respectively. It was intended that period I produced the same metabolic rate as Period III, and Period II the same as Period IV (cf. the design of Flandrois, Lefrancois & Teillac, 1961); see Table 2. In the last minute of each work period mixed expired air was collected as in the bicycle experiments, and the stride rate was counted.

During both bicycle and treadmill exercise the respiratory variables were recorded for each breath during the last 2–3 min of each run. Breaths were excluded if tidal volume exceeded 1·5 times the mean value, or if the inspiratory duration was more than twice the mean. The two breaths following any irregular breath were also excluded. The V_T, T_T, T_I and T_E of the last forty breaths in each run were used in the subsequent calculations. Mean ventilation ($\dot{V}_E$), oxygen uptake ($\dot{V}_{O_2}$) and carbon dioxide output ($\dot{V}_{CO_2}$) were computed for each run. The rectal temperature was measured ½ and 1½ min before the end of each run.

RESULTS

The relation between oxygen uptake ($\dot{V}_{O_2}$) and the intensity of work on the bicycle ergometer is shown for one subject in Fig. 1. Different symbols indicate the rate of pedalling, and whether the observations were made early or late in a 12-min period. The oxygen uptake was usually slightly higher at any given work intensity at 70 rev/min than at 50 rev/min, but the difference remained approximately the same with increasing load. No consistent differences were found between early and late runs. Early and late runs were compared for all subjects by paired tests to determine whether it was legitimate to pool the values. $\dot{V}_{CO_2}$ was not significantly different in any subject; $\dot{V}_E$ was slightly higher in the late runs (mean difference 1·75 l. min^{-1}), and thus a small increase in the ventilatory equivalent for CO_2 resulted (mean difference 0·89); as expected, the rectal temperature was higher in the late runs (mean difference 0·18° C). The small magnitude of these differences would justify, with few reservations, our subsequent pooling of data from the early and the late part of the 12-min work periods.

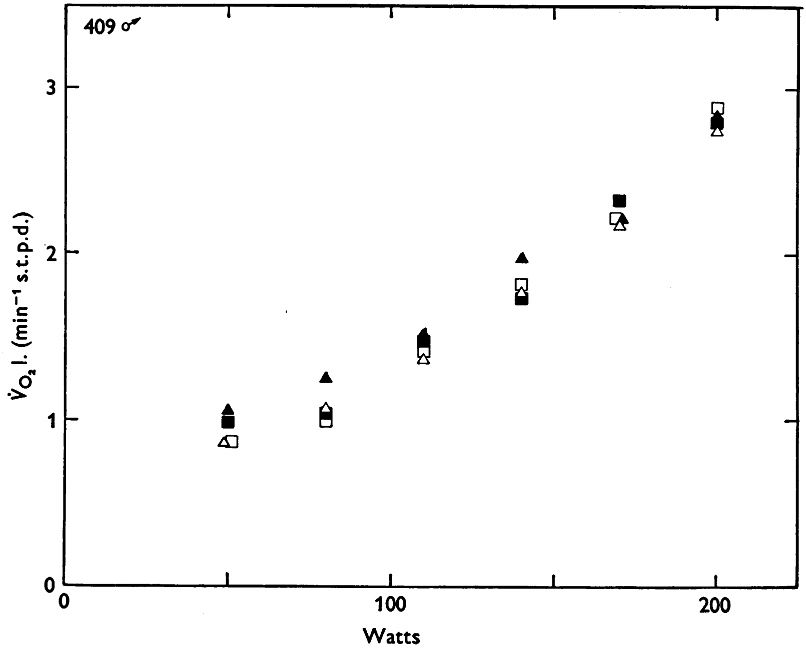

Fig. 1. Oxygen uptake ($\dot{V}_{O_2}$) plotted against the intensity of work (W.) on the bicycle ergometer for subject 409. Runs performed at 50 rev/min: △, early (0–6 min) and □, late (6–12 min); runs performed at 70 rev/min: ▲, early (0–6 min) and ■, late (6–12 min).

In the following analysis of data we have used the output of carbon dioxide as the index of respiratory drive since the data were better described as a function of $\dot{V}_{CO_2}$ than as a function of $\dot{V}_{O_2}$ (see also Wasserman, van Kessel & Burton, 1967).

All the respiratory variables studied are described as linear functions of $\dot{V}_{CO_2}$. Table 1 gives the linear regression statistics of $\dot{V}_E$, T_T, T_I and T_E on $\dot{V}_{CO_2}$ for each subject at each pedalling speed. This makes it possible to test whether the two pedalling speeds affected any of the measured ventilatory variables differently. None of these regressions differed significantly with respect to intercept or slope at the two pedalling rates. (A photostat giving more details of the data and the statistics used is available from the authors on request). The mean pattern of breathing related to carbon dioxide output is therefore indistinguishable at the two pedalling speeds.

Table 1 also shows the regressions with the data from the two pedalling speeds pooled. The individual values, with different symbols for the 50 and the 70 rev/min points, are shown for one subject in Figs. 2, 3 and 4. The linear fit of the different relationships is clearly demonstrated in the

TABLE 1. The linear regressions of $\dot{V}_E$ (l.min^{-1} b.t.p.s.), V_T (l. b.t.p.s.), T_T, T_I and T_E (all msec) on $\dot{V}_{CO_2}$ (l. min^{-1} s.t.p.d.) are shown for each subject at each of the two pedalling rates and with data from the two speeds pooled. The significance of the difference of slope (a) from zero is indicated by stars (***, $P < 0{\cdot}001$; **, $P < 0{\cdot}01$; *, $P < 0{\cdot}05$; n.s., not significant). The two pedalling rates produced no significant difference in the regressions for any of the variables. The units of the slopes (a) are dimensionless

	Pedalling		$\dot{V}_E = a.\dot{V}_{CO_2}+b$		$V_T = a.\dot{V}_{CO_2}+b$		$T_T = a.\dot{V}_{CO_2}+b$		$T_I = a.\dot{V}_{CO_2}+b$		$T_E = a.\dot{V}_{CO_2}+b$	
Subject	rate (rev/min)	n	b (l.min^{-1})	a	b (l.)	a	b (msec)	a	b (msec)	a	b (msec)	a
454	50	12	1·03	26·30***	0·44	0·69***	3030	−500**	1210	−134*	1810	−367**
	70	12	−2·30	28·86***	0·53	0·60***	3060	−570***	1280	−186**	1790	−385***
	Pooled	24	−0·65	27·66***	0·49	0·635***	3060	−546***	1250	−162***	1810	−383***
409	50	12	2·24	24·54***	0·50	0·59***	2690	−310**	1110	−97·7**	1580	−213***
	70	12	3·18	24·25***	0·54	0·55***	2580	−290***	1090	−90·8***	1490	−195***
	Pooled	24	2·66	24·41***	0·52	0·57***	2640	−302***	1100	−94·4***	1540	−207***
438	50	12	2·93	22·84***	0·52	0·60***	3070	−450*	1210	−121*	1860	−331**
	70	12	3·87	21·73***	0·62	0·53***	3000	−400**	1200	−107*	1800	−291***
	Pooled	24	3·63	22·10***	0·58	0·554***	3030	−420***	1200	−111*	1830	−308***
445	50	11	−2·69	34·27***	0·38	0·88***	2820	−400*	1150	−110·0$^{\text{n.s}}$	1670	−291*
	70	11	−6·22	36·60***	0·31	0·89***	2520	−270$^{\text{n.s.}}$	1000	−46·4$^{\text{n..s}}$	1520	−224$^{\text{n.s.}}$
	Pooled	22	−4·56	35·58***	0·35	0·88***	2680	−340**	1080	−81·1*	1600	−259**
439	50	6	−1·80	26·32***	0·48	0·91*	4500	−1020*	1610	−246$^{\text{n.s.}}$	2890	−780*
	70	6	−4·66	28·81***	0·65	0·65*	4440	−1240*	1460	−224$^{\text{n.s.}}$	2990	−1014**
	Pooled	12	−3·12	27·54***	0·61	0·741***	4480	−1228**	1590	277$^{\text{n.s.}}$	3000	−951***

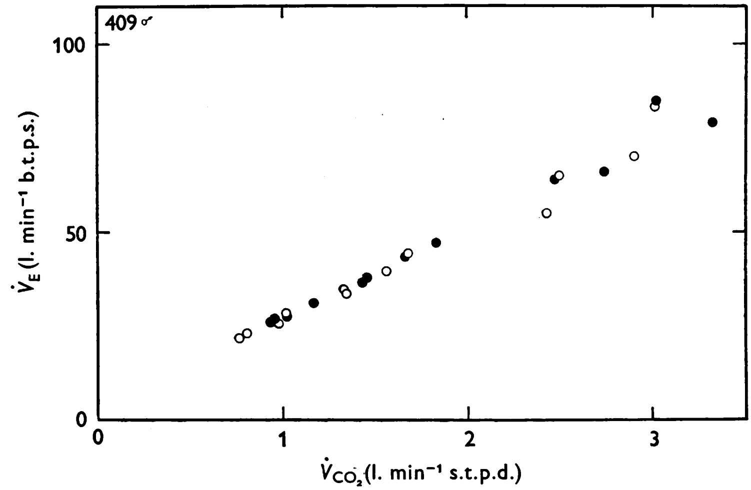

Fig. 2. Minute volume of ventilation ($\dot{V}_E$) plotted against carbon dioxide output ($\dot{V}_{CO_2}$) for subject 409 during bicycle ergometer exercise. ○, runs performed at 50 rev/min; ●, runs performed at 70 rev/min.

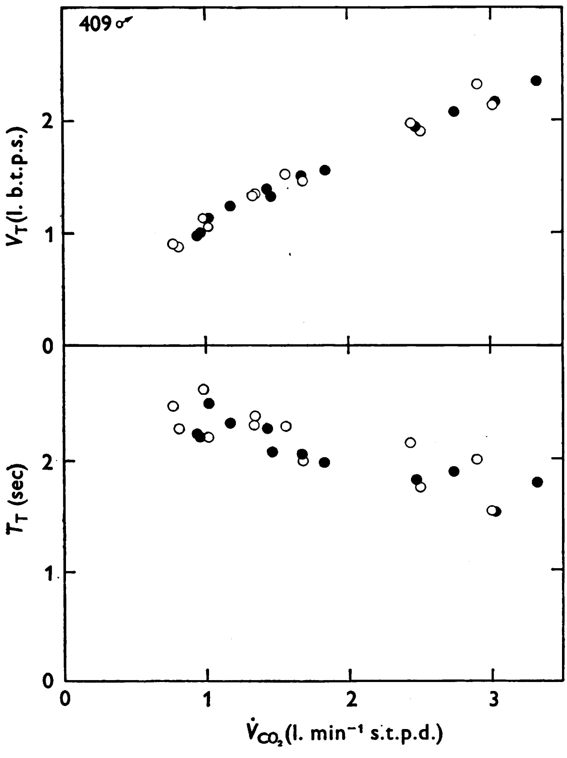

Fig. 3. Tidal volume (V_T) (upper panel) and total breath duration (T_T) (lower panel) plotted against carbon dioxide output ($\dot{V}_{CO_2}$) for subject 409 during bicycle ergometer exercise. ○, runs performed at 50 rev/min; ●, runs performed at 70 rev/min.

Figures. Fig. 4 shows that the major part of the decrease in T_T with increasing $\dot{V}_{CO_2}$ is due to change in the expiratory duration; inspiratory duration changes little but still significantly in four of the five subjects.

The mean pattern of breathing was thus identical at the two pedalling speeds. It is, however, still possible that these mean values were of different composition in the 50 and 70 rev/min conditions. The individual breath durations could have been grouped around exact multiples of the period of rotation of the pedals, and the mean could have resulted as a weighted average of these groups. To test this hypothesis the frequency distribution of T_T of each breath, from all the work loads, was analysed. A bin width of 50 msec was used. The values of T_T which corresponded to simple ratios of pedalling frequency to respiratory frequency (1:1, 2:1, 3:1, 4:1, 3:2, 5:2, 4:3) were calculated. One such frequency distribution is shown in Fig. 5. This selection of ratios was somewhat arbitrary but it seems improbable that any possible link between movement frequency and respiratory frequency should be more complicated. According to the submultiple hypothesis it should be more likely for a breath to have a T_T corresponding to one of these calculated values than not. The mean

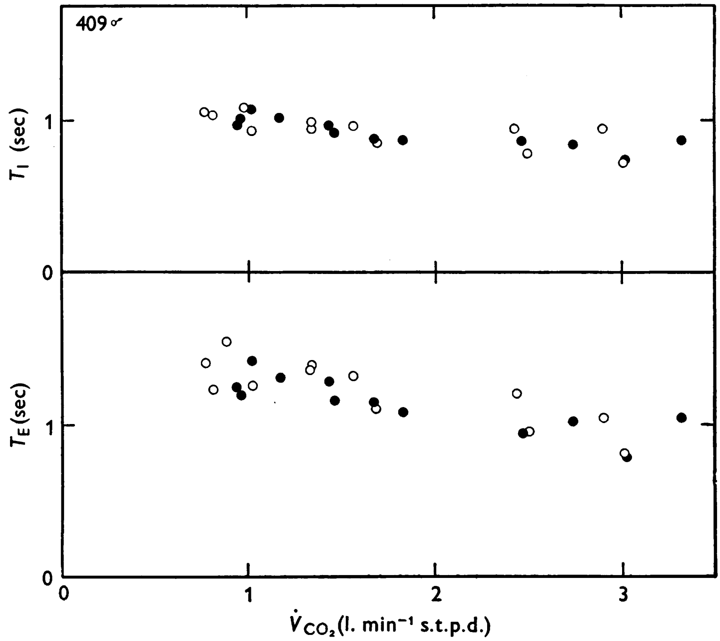

Fig. 4. Inspiratory duration (T_I) (upper panel) and expiratory duration (T_E) (lower panel) plotted against carbon dioxide output ($\dot{V}_{CO_2}$) for subject 409 during bicycle ergometer exercise. ○, runs performed at 50 rev/min; ●, runs performed at 70 rev/min.

contents of bins within 25 msec of these values was not significantly different from that of the other bins ($P > 0{\cdot}2$ in each case). Furthermore the frequency distribution was tested for normality by Kolmogorov–Smirnov's test (Sokal & Rohlf, 1969); of eighteen tested distributions (ten on the bicycle, eight on the treadmill) only three were significantly different ($p < 0{\cdot}05$) from the normal. A third test compared the actual content of the bins corresponding to the simple submultiples with that predicted by the fitted normal distribution; in no subject was a significant deviation found.

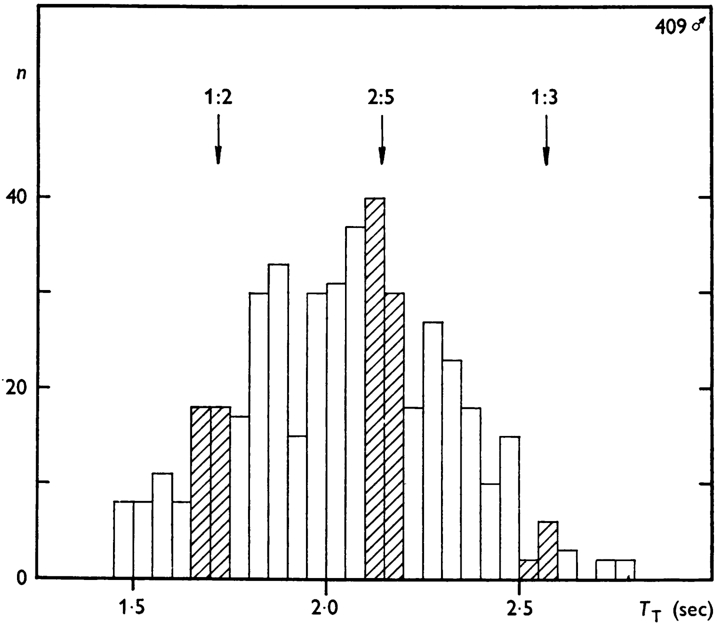

Fig. 5. Frequency distribution of total breath duration (T_T) of all breaths of subject 409 at 50 rev/min on the bicycle ergometer. Bin width = 50 msec. Bins within 25 msec of predicted breath durations are hatched and marked with three of the tested ratios of respiratory frequency to pedalling speed.

In the work loads studied no support for the submultiple hypothesis could thus be found.

The results from the treadmill experiments are shown in Table 2. No clear dependence of mean breathing pattern on striding rate could be found. A comparison of these values with those of Table 1 and Figs. 2, 3 and 4 furthermore suggests that treadmill walking and bicycling result in a similar ventilatory pattern. The data were also examined for evidence of a linkage between stride time and individual breath duration as above. Again, no significant correspondence was found.

TABLE 2. All measured variables during the four conditions on the treadmill for subjects 454 and 409. In the last two columns condition I is compared with condition III, and condition II with condition IV (see Text)

		Speed (km/hr)	Gradient (%)	Step time (msec)	$\dot{V}_{CO_2}$ (l. min^{-1} s.t.p.d.)	$\dot{V}_E$ (l. min^{-1} b.t.p.s.)	V_T (l. b.t.p.s.)	T_T (msec)	T_I (msec)	T_E (msec)	% change step time	% change T_T
454	I	5·2	7	510	1·19	27·7	1·24	2690	1100	1590	−2·0	−8·9
	III	6·1	4	500	1·23	29·8	1·22	2450	1080	1370		
	II	7·2	7	460	1·80	45·6	1·55	2040	890	1150	+10·9	+6·4
	IV	6·2	11	510	1·96	44·9	1·62	2170	980	1190		
409	I	5·3	7	460	1·34	34·5	1·34	2330	990	1340	−6·5	+3·0
	III	6·0	4	430	1·35	34·4	1·38	2400	1020	1380		
	II	7·0	7	410	1·94	49·8	1·65	1990	720	1270	+2·4	+4·5
	IV	6·3	11	420	2·07	52·3	1·81	2080	910	1170		

DISCUSSION

The linear increase in $\dot{V}_{O_2}$ with increasing intensity of work at submaximal levels has often been described; the nature of the linkage remains obscure. $\dot{V}_{CO_2}$ rather than $\dot{V}_{O_2}$ has been used as an index of metabolism in the present work because the relation of $\dot{V}_E$ and $\dot{V}_{CO_2}$ is linear over a wider range than the relation of $\dot{V}_E$ and $\dot{V}_{O_2}$ (Wasserman *et al.* 1967; Torelli & D'Angelo, 1967; Cunningham, 1974).

The finding of a slightly lower mechanical efficiency of work on a bicycle ergometer at 70 rev/min than at 50 rev/min is in agreement with the results of Eckerman & Millahn (1967). The approximately constant $\dot{V}_{O_2}$ difference found at increasing work intensity on comparing the two rates of pedalling would imply that the difference in efficiency decreases with increasing load.

In agreement with Lloyd & Patrick (1963), we found the relation between $\dot{V}_E$ and $\dot{V}_{CO_2}$ to be independent of the pedalling speed. This indicates that frequency of movement *per se* is not a major determinant of ventilation in the steady state (see also Sipple & Gilbert, 1966).

In textbooks and reviews it is often stated that respiratory frequency during rhythmic exercise is determined by the frequency of repetitive movements (e.g. Asmussen, 1965; Dejours, 1967; Åstrand & Rodahl, 1970; Cunningham, 1974). Our experiments were designed to test this hypothesis, since few accessible data support the claim. Our results give no support to this submultiple hypothesis during submaximal bicycle ergometer work (50–200 W) at a pedalling speed of either 50 or 70 rev/min. Kelman & Watson (1973) came to the same conclusion for work on a bicycle ergometer, but do not present any relevant data. During treadmill running Bannister *et al.* (1954) found that the respiratory frequency was always a submultiple of the stride rate. An important difference, however, exists between their and the present procedure. They asked their subjects to stride in time with a metronome, while we used no rhythmic signal. If a subject is conscious of the rhythm (as in listening to a metronome, watching a flashing light, or concentrating on respiratory rhythm) it seems more likely that he might entrain his breathing.

Flandrois *et al.* (1961) studied the effect on breathing of different speeds and gradients on the treadmill. They found a trend to higher respiratory frequency with higher speeds of running in isometabolic conditions in two of their three subjects (the authors); this trend was only marked in one of the two (see Dejours, 1967). No such trend was observed in our naive subjects.

Our method of keeping the pedalling rate constant is imperfect, and the prediction of 'exact ratio' breath durations used in the first of the three methods of testing the distribution of T_T is therefore potentially unreliable. However, the true pedalling speed as observed by the experimenters varied by less than ± 2 rev/min. This corresponds to a typical maximal error in T_T of ± 80 msec. The width of two bins in our frequency distribution of T_T is 100 msec, and thus the method is little affected by this slight variation in the pedalling speed. The two last methods should not be affected by this variation.

The similarity of the ventilatory variables related to $\dot{V}_{CO_2}$ in bicycle ergometer work at two speeds and treadmill walking at different combinations of speed and gradient, implies that the selection of $\dot{V}_T$, T_I and T_E is not affected by the force or speed of muscle contractions, but is a unique property of the ventilatory system related to the metabolic demands of the body (cf. Davies & Sargeant, 1974). Any neurogenic drive to ventilation in the types of exercise which we have studied, therefore, whether central or peripheral, must be very closely related to the metabolism. However, work done by different muscle groups does not produce a unique relationship between metabolic rate and ventilation (Asmussen & Nielsen, 1946; Jensen, 1972).

Passive movements of the limbs and trunk produced no linkage of respiratory rate to the movement frequency in the study of Dixon, Stuart, Mills, Varvis & Bates (1961).

In running the vertical oscillation of the abdominal contents might act as a piston and make it energetically more convenient for the subject to link his breathing and striding rates. It is essential for a crawl swimmer to breathe in time with his arm movements. Selection of breathing pattern in these circumstances or in any more exhaustive type of exercise or work could be a learned process, differing in kind from that in bicycling or treadmill walking of submaximal intensity. It is also possible that the total drive in the types of rhythmic exercise studied by us may be smoothed, and that other types of exercise exist where a phasic total drive affects breathing pattern differently.

In conclusion we have found no link between movement frequency and respiratory frequency for bicycle exercise and treadmill walking of submaximal intensity except through the metabolic rate. The selection of breathing pattern, therefore, seems to be independent of the nature of the drive.

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