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AN EVALUATION OF A TREADMILL WORK TEST

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INTRODUCTION

Since oxygen uptake is a major determinant of physical work capacity, the measurement of maximum oxygen consumption provides a means not only of determining an individual's capacity to perform work, but also of comparing work capacity between individuals. The present report describes the application of the Bruce treadmill protocol (Bruce, Blackman and Jones, 1963; Froelicher, Brammel, Davis, Noguera, Stewart and Lancaster, 1974), slightly modified, to the measurement of maximum oxygen uptake in a group of fourteen subjects.

METHODS

The Bruce Protocol

The format of the Bruce protocol is shown in Fig. 1. Although the protocol allows for continuous step increases in work load up to a treadmill speed of 8.9 $km.hr^{-1}$, and 20% incline, this final sixth stage was omitted in the present study. The first and fifth stages respectively, were preceded and followed by 5 min periods seated at rest. Throughout the 25 min experimental period measurements were made continuously of oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), ventilation volume ($\dot{V}_E$), and heart rate (fH). Additionally, in 5 subjects, an electrocardiogram (ECG) was recorded continuously from electrodes located over the body of the sternum, over the cardiac apex, and at the lateral 1/3 of the clavicle.

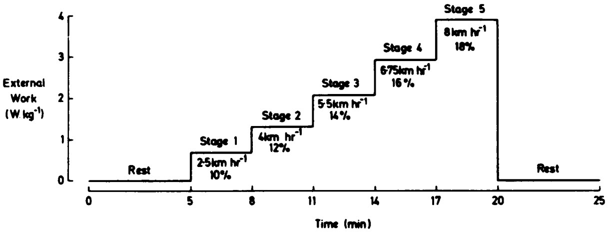

Fig 1: Format of the treadmill protocol.

The Treadmill

The external work (W) accomplished during treadmill exercise is a function of the total body weight (BW), including clothing and any loads carried, and the treadmill speed (v) and incline (i). Thus:

$$W = 10^3 \; (BW \times v \times i)/6.12 \times 60 \times 100 \qquad (1)$$

where BW is in kg, v in $km.hr^{-1}$, and i in % (ie, grade of x% is a vertical displacement of x units for every 100 units of belt movement). The factor 6.12 converts $kg.m.min.^{-1}$ to watts. Figure 2 provides work output in $W.kg^{-1}$ for belt speeds of 0 to 16 $km.hr^{-1}$ over a range of commonly used grades.

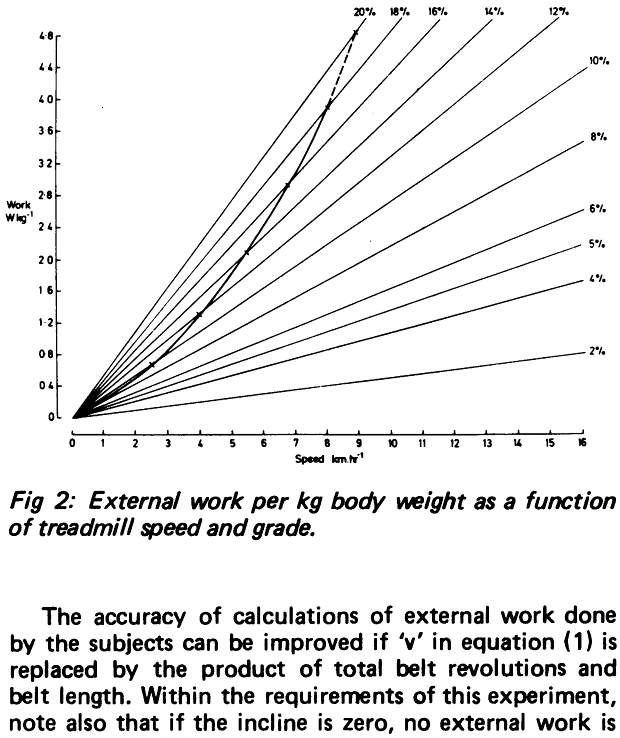

Fig 2: External work per kg body weight as a function of treadmill speed and grade.

The accuracy of calculations of external work done by the subjects can be improved if 'v' in equation (1) is replaced by the product of total belt revolutions and belt length. Within the requirements of this experiment, note also that if the incline is zero, no external work is performed, although clearly energy is expended in raising and lowering the limbs, and in accelerating and decelerating the limbs (Wilkie, 1960).

Subjects

Of the 14 subjects, 2 were women. Ages ranged from 17 to 41 years. All tests were carried out at least 2 hours after the last meal had been taken, and the environmental conditions were always similar (∿ 22 °C dry bulb, and 50% relative humidity). Shorts, vest and running shoes were worn.

The subjects were not allowed to support themselves using the treadmill hand-rails during the 3 min perids of data collection, but they were allowed to do so during the transition from one stage to the next (this requiring approximately 10 s), and when they became exhausted and unable to continue.

Gas Collection

For the collection of expired gas, one of the following two assemblies was worn by the subjects:

i. A noseclip and a standard rubber mouthpiece (inside cross sectional area 180 mm^2) attached to a low resistance valve box with mica disc valves (P. K. Morgan, Rochester, Kent).

ii. A modified RAF oronasal mask (P/Q series).

The mouthpiece and valve box were supported by a counterbalance device similar in design to that described recently by Ellis and Lampman (1976) and which gave good freedom of movement; the mask was supported by the adjustable hooks on a RAF Type G cloth flying helmet. To reduce breathing resistance at high air flows the mask was modified by:

a. replacing the inspiratory and anti-suffocation valves by low resistance, spring-loaded mica valves;

b. replacing the compensated expiratory valve by a uncompensated rubber mushroom valve (Clement Clark Ltd);

c. occluding the compensation tube.

The expirate from the valve box or mask passed via a Y-piece and two parallel 0.6 m lengths of flexible nylon hose, with smooth inside bore (Penlon; i.d. 21 mm) to a mixing box (volume 2.175 ℓ) and finally to a dry gas meter (Parkinson Cowan) on which was mounted a spindle shaft encoder (Leine and Linde, Solna, Sweden).

The resistance of the gas collection circuit using the mouthpiece, and using the oronasal mask is given in Fig. 3.

Gas Analysis

A sample port was located immediately downstream of the mixing box. Continuous gas analysis was performed by one or other of two methods:

a. *Mass spectrometry.* Gas was drawn through a heated probe (at 60 ml.min^{-1}) to a Centronics quadrupole mass spectrometer. The output of the spectrometer was displayed on a direct-writing hot stylus pen recorder (Devices Ltd). The output of the digital shaft encoder of the gas meter was fed to a summing and timing circuit, and the resultant output each minute displayed by the pen recorder in Binary Code Decimal form. No correction was made for the expired gas removed by the mass spectrometer.

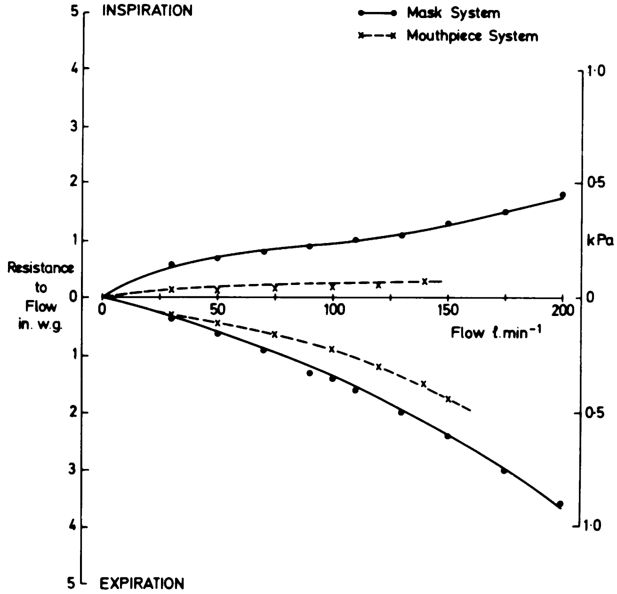

Fig 3: Resistance to flow of the expired gas collection circuit.

b. *Polargraphic O_2 and Infra-Red CO_2 Analysis.* Gas was drawn through a drying tube containing desiccant (silica gel), and then through heated, sample lines to the heads of a polarographic oxygen analyser (OM-11, Beckman RIIC Ltd), and an infra-red carbon dioxide analyser (LB-2, Beckman RIIC Ltd). The sample flow rate for each analyser was set a 0.5 ℓ.min^{-1}, and the output of the gas meter was subsequently corrected for this loss of 1 ℓ.min^{-1}. The output of the analysers and the shaft encoder was obtained every minute in digital form from a data logger (Solartron Ltd).

Calibration of the mass spectrometer and the Beckman analysers was carried out with gases analysed using Lloyd Haldane apparatus, which spanned the expected range of expired O_2 and CO_2 concentrations. The output of the digital shaft encoder was calibrated by forcing known volumes of air through the gas meter. By observing the time taken to respond to a step-change in the concentration of a steady flow of gas, the delay time imposed by the expiratory circuit was shown to be 40 s at 5 ℓ.min^{-1}, falling to 8 s at 50 ℓ.min^{-1}, and 5.5 s at 100 ℓ.min^{-1}.

The results showed no evidence of any systematic difference between the two methods of gas analysis.

Calculation of Results

The pulmonary ventilation ($\dot{V}_E$ in ℓ (BTPS).min^{-1}), oxygen uptake ($\dot{V}O_2$) and carbon dioxide output ($\dot{V}CO_2$) in ℓ (STPD).min^{-1}, and the Respiratory

Exchange Ratio (R) were calculated after 1, 2 and 3 min of exercise from values of $\dot{V}_E$ in ℓ (ATPS).min^{-1}, and from values of the fractional concentrations of O_2 and CO_2 (FO_2 and FCO_2).

Methodological Errors

Ventilation volumes were measured with the gas meter to within 0.5 ℓ.min^{-1}. Thus, the errors introduced into calculations of $\dot{V}O_2$ and $\dot{V}CO_2$ by $\dot{V}_E$ were greatest at rest (ie ± 5 to ± 10%), the percent error decreasing as a reciprocal function of increasing $\dot{V}_E$. The major factor limiting the accuracy of the FO_2 and FCO_2 determinations with the mass spectrometer was the ± 1% full scale resolution of the pen recorder trace. For calibration gases spanning a range of 12 to 21% O_2 and O to 6.7% CO_2, the respective accuracies were ± 0.9% and ± 0.7%.

The manufacturer's specification for the polarographic O_2 analyser indicated an accuracy of ± 0.7% of full scale (0 to 25% O_2), and for the infra-red CO_2 analyser an accuracy of ± 2% of full scale (0 to 10% CO_2). However, repeated calibrations of these analysers at approximately ½ hr intervals were reproducible to within ± 0.2% of full scale for O_2, and ± 0.1% of full scale for CO_2.

RESULTS

Since the object of the work tests was to determine maximum O_2 uptake, no data are presented relating to $\dot{V}_E$ and $\dot{V}CO_2$, although these were used in calculating $\dot{V}O_2$ and R.

O_2 Uptake

Oxygen uptakes at the highest work rate that could be sustained for at least 1 min ranged from 38 to 73 ml.kg^{-1}.min^{-1}. Although the magnitude of the step increments in work load were not equal (see Fig 1), $\dot{V}O_2$ was related linearly to work output in 8 of the 14 subjects. In the remaining 6 subjects $\dot{V}O_2$ tended to approach a plateau at the highest work load (see Fig 4a for representative data).

Steady state values for $\dot{V}O_2$ were not achieved after 1 min, or 2 min of exercise (Fig 5). It is possible therefore that maximum values for $\dot{V}O_2$ had not been achieved after 3 min at each of the work loads.

Respiratory Exchange Ratio (R)

Resting values for R ranged from 0.7 to 0.9. During the first and second stages of the work test R consistently decreased below resting values, then increased to between 0.8 and 1.0 as the work load further increased, and rose above 1.0 at the limit of work capacity. Particularly during the early stages of recovery R rose substantially above 1.0.

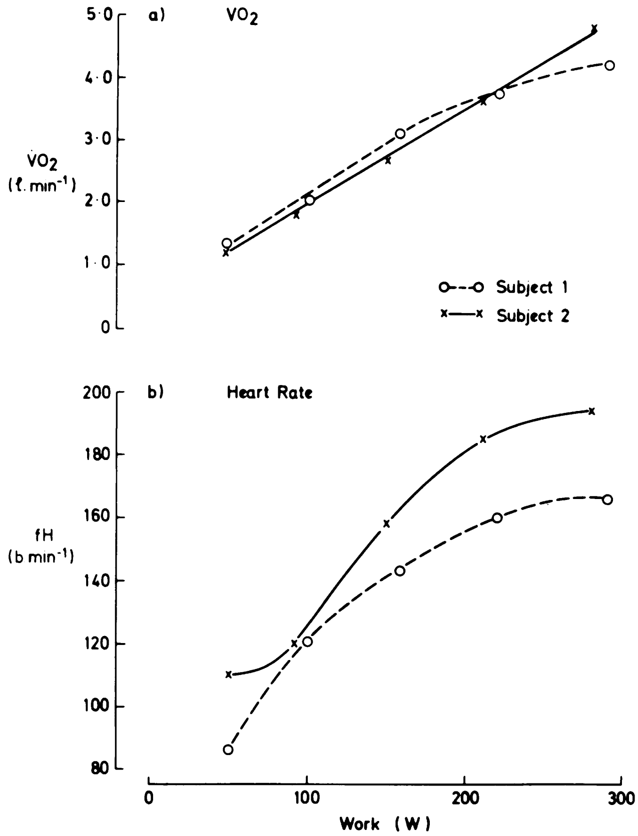

Fig 4: Variation of (a) $\dot{V}O_2$, (b) fH as a function of external work in 2 subjects.

ECG

The quality of the ECG obtained both at rest, during exercise, was considered to be good. Even at the higher work rates movement artifact was small, with little EMG interference. The records were adequate for clarifying possible disorders of rhythm, although probably not for identifying significant ST segment depression.

Heart Rate

Maximum heart rate ranged from 163 to 220 b.min^{-1}. Submaximal heart rates were not related linearly to work load in any subject. Consequently plots of fH against $\dot{V}O_2$ were also non-linear (see Fig 4b for representative data).

DISCUSSION

Gas Collection

After the first six subjects had carried out the treadmill work test it was apparent that in the fittest of these, work capacity was being limited by the difficulty of maintaining adequate ventilation through the mouthpiece and valve box, and not by the achievement of $\dot{V}O_2$ max. Replacing the mouthpiece assembly with a modified oronasal mask as described (see Methods) afforded a dramatic improvement in subjective comfort, particularly at high work rates when ventilation volumes exceeded 80 ℓ.min^{-1}. This improvement cannot be explained in terms of a reduced resistance in the respiratory circuit since both the inspired and the expired flow resistance were actually greater (Fig 3). Dead space volumes were very similar for the two systems — 50 ml for the mouthpiece and valve box, and 70 ml for the face mask. An important difference between the systems, however, is that whereas the mouthpiece can only be held securely in position by gripping with the teeth, and hence tending to keep the mouth closed, the oronasal mask allows normal respiration through the open mouth and nose. Resistance to air flow is therefore likely to be substantially higher with the mouthpiece for large values of $\dot{V}_E$.

Although the use of oronasal masks for collecting expired air is often considered inappropriate because of the danger of leaks, no such difficulties were encountered in the present study. Leaks should not be a problem if the mask is fitted correctly, and tightly, around the face. Furthermore, even very small leaks can generally be detected promptly by the subject, and corrective action taken.

Gas Analysis

Although two methods of gas analysis were used in the present study, consideration of the errors involved in the measurement of $\dot{V}_E$, FO_2 and FCO_2 indicates that the overall error was probably very similar for both methods. Under strictly controlled conditions maximum $\dot{V}O_2$ can be measured to within ± SD 3% (Taylor, Wang, Rowell, and Blomqvist, 1963; Åstrand, 1967), this comparing with ± SD 7.5% when maximum $\dot{V}O_2$ is predicted from submaximal heart rates (Davies, 1968). The large error in the indirect measurement of maximum $\dot{V}O_2$ arises from the asymptotic nature of the $fH/\dot{V}O_2$ curve (Wyndham, Strydom, Maritz, Morrison, Peter, and Potgieter, 1959; Davies, 1968).

An important practical difference in the analysis of expired gas by mass spectrometry, and by polarographic O_2 and infra-red CO_2 analysers, is that in the latter it is usual to dry the expirate before analysis. An error can then be introduced if the desiccant becomes saturated, the partial pressure of the gas being analysed falling relative to the total pressure. Another point to note is that concern has been expressed recently that silica gel is not inert to CO_2, and some authorities now recommend magnesium perchlorate (C. T. M. Davies; personal communication).

Critique of the Bruce Protocol

According to Bruce et al (1963), their treadmill work test is intended to provide an evaluation of cardiopulmonary function during exercise, and not an evaluation of physical fitness (although the rationale beind the distinction is not clear). However, only 4 of the present group of subjects were able to complete the test, and they were sufficiently exhausted to justify the assertion that had the final sixth stage of the protocol been included, they would probably have not completed the test. Furthermore, the $\dot{V}O_2$ measured at the third minute of stage 5 ranged from 65 to 73 ml.kg^{-1} — ie, values substantially higher than the (adult) male population mean of ∿45 ml.kg^{-1}, and typical of fit athletes undertaking regular exercise (Cumming, 1967; Saltin and Åstrand, 1967). It may be concluded, therefore, that the Bruce protocol *does* allow physical fitness levels to be compared in terms of $\dot{V}O_2$. What the protocol does not allow (except in very unfit individuals) is the positive demonstration that a maximum $\dot{V}O_2$ has been achieved, for this requires at least three determinations of $\dot{V}O_2$ at a plateau level (Taylor, Buskirk and Henschel, 1966; Wyndham et al, 1959; Davies, 1968). In the present study, although a clear tendency towards a $\dot{V}O_2$ plateau was noted in 6 subjects, a horizontal asymptote was never observed. Froelicher et al (1974) have reported an absolute plateau in only 22% of 127 subjects following the Bruce protocol.

Even if positive evidence for the attainment of maximum O_2 intake is lacking, a considerable body of circumstantial evidence may be available indicating that a maximum $\dot{V}O_2$ has been achieved. For example, if the subject stops exercising because of total exhaustion it is difficult not to conclude that the $\dot{V}O_2$ measured immediately prior to collapse does represent a maximum. Also, R is consistently in excess of unity at this point, again indicative of a very high level of exercise (Issekutz, Birkhead, and Rodahl, 1962), and fH is generally within ± 10 b.min^{-1} of the predicted maximum (Åstrand, 1960). On the basis of such circumstantial evidence it is considered that a value of $\dot{V}O_2$ close to maximum was measured in all the present subjects who failed to complete the work test.

An interesting feature of the heart rate measurements was the consistent non-linear relationship with work rate (Fig 4b). For most types of work this relationship is linear (Åstrand and Rodahl, 1970), and forms the basis of many submaximal tests for estimating maximum O_2 uptake (Wyndham, 1967). However, the present data would suggest that the step treadmill test as used here is unsuitable for the prediction of maximum $\dot{V}O_2$ from cardiac frequency measurements. The explanation for the non-linearity may lie with the similar non-linear relationship between energy expenditure and speed of walking (Margaria, Cerretelli, Aghemo and Sassi, 1963), although this suggestion is difficult to reconcile with the essential linearity of the submaximal $\dot{V}O_2$/work load relationship (Fig 4a).

The values for $\dot{V}O_2$ measured at stages 4 and 5 in the present study were some 40 to 50% higher that those reported by Froelicher et al (1974), for subjects following an identical work protocol. Calculations from Froelicher's data imply that as walking speed increased, and running became necessary, so mechanical efficiency increased, approaching 30% in one subject at stage 6. This is inconsistent with the observations of Margaria et al (1963), who noted that mechanical efficiency was greatest at slow walking speeds. The results of Froelicher et al are clearly anomalous, and the explantion appears to be that their expired gas collections, which were made into neoprene balloons over consecutive one minute periods, were not obtained under steady state conditions. Figure 5 shows that a respiratory steady state is apparently only rarely achieved during the 3 min exercise periods at each stage of the work test. Consequently analysis of a mixed 1 minute expired gas collection will provide an average value for F_EO_2 which is less than the value for F_EO_2 after 1 minute. The apparently increasing mechanical efficiency is therefore a manifestation of anaerobic energy expenditure, and an accumulating oxygen debt.

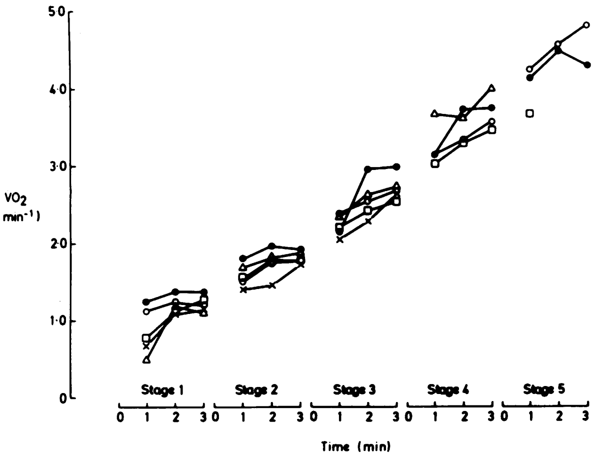

Fig 5: Oxygen uptakes after 1, 2 and 3 min of exercise at each of the 5 stages of the treadmill work test for 5 subjects. A female subject is identified (x).

Calculations of efficiency from the present data using values for $\dot{V}O_2$ measured at the end of the 3rd minute of each stage, although more consistent with Margaria's results, do show a large between-subject variability not explicable purely in terms of differences in athletic skill. Again, the explanation appears to be that the calculations are based on non-steady state measurements of $\dot{V}O_2$.

These considerations prompt two conclusions. First, if expired gas analysis is to be carried out under non-steady state conditions, bag collections are useless, and continuous monitoring of F_EO_2 is mandatory. Second, mechanical efficiency cannot be calculated from measured $\dot{V}O_2$ (see also Wilkie, 1960).

Two features of the Bruce protocol were consistently criticised by the subjects. First, the treadmill gradient at stages 4 and 5 caused a localised fatigue in leg muscles which was sometimes sufficiently severe to be the major factor determining the termination of the work test. Second, at stage 4 subjects found it difficult to decide whether it was better to walk fast, or to run slowly.

In general, it appears that either the gradient or the speed should be varied in a treadmill work test, but not both. From the experience of the present study the maximum gradient should not exceed 14%. Also, because of the variation in mechanical efficiency with walking speed, and the constancy of energy expenditure per kg per m (Margaria et al, 1963), it is probably better to set a minimum treadmill speed such that all subjects must run. Since one of the present subjects still preferred to walk at stage 5 (8 km.hr^{-1}), a safe minimum would appear to be 10 km.hr^{-1}. Saltin and Åstrand (1967) have suggested raising the treadmill gradient by 2.6% (1½°) every 3 min from a predetermined value, and maintaining a constant minimum treadmill speed of 10 km.hr^{-1}. With this regime no one can run for longer than 7 min, and a measure of maximum $\dot{V}O_2$ is guaranteed (Saltin and Åstrand, 1967). This protocol requires, however, that an estimate of $\dot{V}O_2$ max be obtained from a preliminary sub-maximal work test in order that the initial treadmill gradient can be set accordingly. Oxygen uptake must be measured continuously. It is also important that the subject be allowed an initial warm-up of 5 to 10 min at 50% of estimated $\dot{V}O_2$ max immediately prior to the test (Åstrand and Rodahl, 1970).

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