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PREDICTABILITY OF $\dot{V}O_2$ MAX FROM SUBMAXIMAL CYCLE ERGOMETER AND BENCH STEPPING TESTS

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ABSTRACT

The predictability of the maximal oxygen uptake ($\dot{V}O_2$ max) was studied using progressive and steady state protocols for cycle ergometry and bench stepping. The subjects were 12 healthy men, 23-58 years old. Prediction of $\dot{V}O_2$ max was made by extrapolation of the heart rate and O_2 uptake at several sub-maximal work-loads using the least squares regression technique. The four sub-maximal procedures underestimated the measured $\dot{V}O_2$ max by between 0.13-0.55 $l.min^{-1}$. The differences between the measured and predicted values were statistically significant for the tests involving the steady state protocol. The correlation co-efficients between the predicted $\dot{V}O_2$ max for each of the submaximal tests, and the measured $\dot{V}O_2$ max, were significant at the .05 level. The results indicate that for a group of male subjects $\dot{V}O_2$ max can be predicted using the progressive protocol on either the cycle ergometer or stepping bench. Individual predictions are liable to considerable error.

Key words: $\dot{V}O_2$ max prediction, Heart-rate, O_2 uptake, Steady state, Progressive.

INTRODUCTION

Cardiorespiratory fitness is commensurate with the ability of the body to take up and use oxygen, and the internationally accepted reference standard for cardiorespiratory fitness, despite recent criticisms (Harrison et al, 1980; Hardman and Williams, 1983), is the maximum oxygen uptake ($\dot{V}O_2$ max). However, while the criteria for cardiorespiratory fitness are generally agreed the method of assessment is more controversial. Ideally, $\dot{V}O_2$ max should be measured directly by requiring subjects to exercise to exhaustion, but with normal adult populations this procedure is not possible both because of the potential risk involved in maximal testing of normal adults and because of the difficulty in motivating such individuals to undertake exhausting exercise. Consequently tests have been developed which estimate $\dot{V}O_2$ max from physiological responses to measured sub-maximal exercise. The most popular methods of sub-maximal testing have been those which predict $\dot{V}O_2$ max by extrapolation from the relationship of sub-maximal $\dot{V}O_2$ and heart rate values to an assumed age-related maximal heart rate.

The different kinds of tests and many variations of procedure make it difficult to select that which is most suited to the survey in question. The two main variables are protocol and mode of exercise. The stepping bench and the stationary cycle are generally favoured as the most suitable ergometers for sub-maximal exercise tests (Shephard, 1978), whilst protocols have varied from the single-level load (Åstrand and Ryhming, 1954) through steady state incremental tests (Maritz et al, 1961; Anderson et al, 1971) to progressive incremental protocols (Thompson, 1977). The present study was designed to test the validity of progressive and steady state protocols using a stepping bench and cycle ergometer to predict $\dot{V}O_2$ max in an adult male population.

METHODS

The subjects comprised 12 physically active students and staff from the University. Details of ages, heights and weights are given in Table I. Prior to acceptance for the study, all subjects completed the Physical Activity Readiness Questionnaire (Chisholm et al, 1975), gave written informed consent, received clearance from their doctor, and underwent a resting ECG.

Table I Physical characteristics of the subjects (mean ± S.D. and range).

Age (yrs)	32.07 ± 10.2	(23.0- 58.6)
Height (cm)	175.7 ± 8.0	(161.5-186.5)
Weight (kg)	72.4 ± 8.9	(56.4- 84.5)

Sub-maximal Tests. Each subject performed four sub-maximal tests, two step tests and two cycle ergometer tests, in random order, on separate occasions, but at the same time of day. The cycle ergometer tests were performed using a Siemens-Elema electrically braked constant-mode ergometer (Model 380B). The step tests were conducted on a specially constructed double 9" stepping bench (Shephard, 1977). Two different step-incremental continuous test protocols were employed, a progressive and a steady state, designed to bring each subject to a heart rate within 10 b.p.m. of 83% of the mean maximal heart rate for his age-group (Åstrand and Rodahl, 1977) corresponding to 75% $\dot{V}O_2$ max (Hellerstein and Ader, 1971).

Workloads. Initial, intermediate and final workloads were adjusted to try and produce a gradual increase in workload from 40-75% $\dot{V}O_2$ max. For each of the step tests a separate tape was recorded for each age-group which included instructions together with a series of metronome beats corresponding to the increasing stepping cadence for the specific test.

Progressive Protocol. Work intervals of 1 minute duration were used at five different work loads. Subjects not attaining the target heart rate were required to work for a further interval of one or two minutes. Expired air samples were collected during the last 30 seconds of each workload. Heart rate was recorded at the end of each workload.

Steady State Protocol. An initial work interval of 3 minutes was followed by two additional work intervals each of 2.5 minutes duration. Subjects not attaining the target heart rate were required to work for a further interval of 2 minutes.

Expired air samples were collected during the final minute of each workload. Heart rate was recorded at the end of each workload.

Prior to each of the sub-maximal tests the subjects were measured for height and weight and then proceeded to rest, supine, for 10 minutes. No attempt was made, however, to achieve basal levels.

Tests were conducted at temperatures ranging from 20-25°C (mean = 22°C) and humidity levels of 48-78% (mean = 64%). A table fan was directed at the subjects during each of the tests as suggested by Shephard (1977). All measurements were made at least 1.5 hrs after eating and all subjects completed the testing programme within 21 days.

Expired air samples were collected through a low resistance two-way respiratory valve (Hans Rudolf 2600) connected to Douglas bags (100 and 150 litre capacity) through a minimum length of lightweight wide-bore tubing (30 mm) via a three-way sliding valve. The volume of each expired air sample was determined by evacuating the contents of each air-bag through a dry gas meter (Harvard) previously calibrated. The percentages of carbon dioxide and oxygen in each sample were determined using an infra-red CO_2 analyser (P. K. Morgan 801D) and a paramagnetic O_2 analyser (Taylor-Servomex OA570). Both analysers were calibrated before each series of analyses with nitrogen, room air and a reference gas, the composition of which had previously been determined by the Lloyd-Haldane technique. All analyses were completed within 30 minutes of collection.

Familiarisation. The testing programme was preceded by a familiarisation session which consisted of a three minute exercise test on the stepping bench using the progressive protocol, followed (after a 5 minute rest) by a six minute single level load on the cycle ergometer from which the subject's $\dot{V}O_2$ max was predicted (Åstrand and Rhyming, 1954). Using this predicted $\dot{V}O_2$ max the treadmill speed was set, as suggested by Åstrand and Rodahl (1977), for a ten minute run at a level inclination. During the final two minutes, expired air samples were collected in order to assess the accuracy of the collection and analyses procedures, on the assumption that the subjects should have reached a steady state. The mean difference between the measured values for the ninth and tenth minutes was 1.2% (mean individual difference 3%) which compares favourably with other studies (Williams and Nute, 1983).

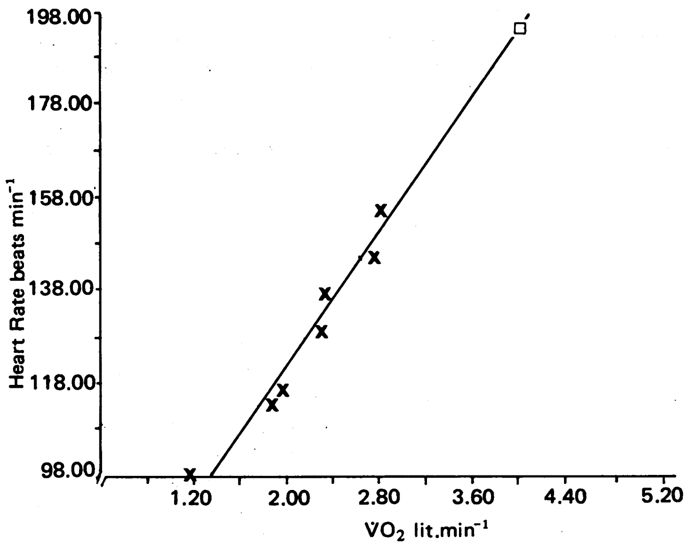
Maximal Test. To establish criterion values maximal exercise tests were conducted on a Quinton Treadmill (Model 18-49D1). The method for determining $\dot{V}O_2$ max was a modified version of that described by Åstrand and Rodahl (1977). After a 5 minute warm-up of level running (at the same speed as for the familiarisation session) the subject rested for 10 minutes on a couch. The subject then exercised at a constant speed and with the treadmill incline at an initial slope of 1.5% which was increased by 1.5% every minute until the subject was unable to continue. Expired air samples were taken during the last 20 seconds of each step increment and during the final 20 seconds signalled by the subject as he neared exhaustion. Heart rate was recorded every 30 seconds using an Exersentary heart rate monitor (Respironics Ltd.).

Finger tip blood samples were taken from a pre-warmed finger 2 minutes and 5 minutes after the test and analysed for blood lactate concentration using the procedure of Henry (1974).

The criterion of maximal effort included an oxygen uptake plateau, such that consecutive workloads increased $\dot{V}O_2$ by less than 150 ml/min, a respiratory quotient greater than 1.0, a final heart rate within 2 S.D. of the expected maximum, and peak blood lactate levels in excess of 8 mmol/L (Åstrand and Rodahl (1977)).

STATISTICAL ANALYSES

The raw data for each subject were processed using a Burroughs 6930 computer using standard procedures (Consolazio et al, 1963). The least squares regression equation was used to plot heart rate against oxygen uptake and extrapolated to a maximum heart rate of 220 beats min^{-1} minus age in years as suggested by Åstrand and Rodahl (1977) (Fig. 1). Means and Standard Deviations were computed for each of the tests, together with correlations (Pearson's Product Moment) and 't' tests (Student's paired) between the measured and predicted $\dot{V}O_2$ max values using the Statistical Package for the Social Sciences (Norusis, 1982) (Table II). An analysis of variance was computed for body weight, temperature and humidity for the sub-maximal tests using the same statistical package. Significance was assumed at the 0.05 level.



Linear Regression Gives: $\dot{V}O_2$ = 0.278 * Heart Rate – 1.3702
Estimated $\dot{V}O_2$ max (at 193 beats min^{-1}) = 3.99 $lit.min^{-1}$
56.8 $ml.kg.min^{-1}$

Fig. 1: Subject P.1 (27 years) cycle ergometer progressive protocol.

RESULTS

Means and standard deviations for the measured and predicted $\dot{V}O_2$ max values are given in Table II. Two subjects who failed to achieve the criteria for the maximal test did so when the test was repeated, their results being, however, almost identical on both occasions. In both cases the higher value was taken as being the true $\dot{V}O_2$ max.

Comparison of the predicted values with the measured $\dot{V}O_2$ max revealed that all four sub-maximal test protocols underestimated the measured value by between 0.13 and 0.55 $l.min^{-1}$. However, while the difference between the measured and predicted scores for the two progressive protocols was non-significant the difference was significant at the .01 level for the steady-state tests. Correlation coefficients proved significant between each of the four sub-maximal test procedures and the measured maximum value with the cycle steady-state protocol relationship being significant at the .001 level.

The analysis of variance computed for body weight, temperature and humidity for the four sub-maximal tests produced F-ratios below the required 2.56 for significance at the 0.05 level.

Table II Relationship of measured to predicted $\dot{V}O_2$ max for 12 male subjects, using progressive (A) and steady state protocols (B) on a cycle ergometer and stepping bench. Extrapolation to maximal heart rate: (Astrand and Rodahl, 1977).

Measured $\dot{V}O_2$ max $l.min^{-1}$	Predicted $\dot{V}O_2$ max ($l.min^{-1}$) Bicycle A	Bicycle B	Step A	Step B
4.14 ±0.68	4.01 ±0.63	3.76 ±0.66	3.84 ±0.60	3.59 ±0.58
Correlation Coefficient	0.67 $p < 0.02$	0.84 $p < 0.001$	0.72 $p < 0.01$	0.66 $p < 0.02$
't' test	0.86 n.s.	3.54 $p < 0.01$	2.19 n.s.	3.64 $p < 0.01$

± S.D.

	Systematic Error (S.E.) and Standard Deviation (S.D.) $l.min^{-1}$ Bicycle A	Bicycle B	Step A	Step B
S.E.	−0.13	−0.39	−0.31	−0.55
S.D.	0.53	0.38	0.48	0.53

DISCUSSION

The basis for the prediction of $\dot{V}O_2$ max from the extrapolation of the sub-maximal relationship between oxygen uptake and heart rate values rests on two major assumptions. First, that the heart rate is linearly related to oxygen uptake over a wide range of work-loads from 50-100% of oxygen consumption and secondly that all subjects within a population age-group are able to reach similar maximal heart rates. Sufficient evidence exists to support Wyndham's (1968) statement that the error arising from the latter asumption is insignificantly different from that to be expected from the random day-to-day variation in the measurement of heart rate and $\dot{V}O_2$ (Davies, 1968). Indeed, in the present study, substituting the maximal heart rate for that suggested by Anderson et al (1971) for each age-group revealed no significant difference in the extrapolated results. However, several authors have shown that the linear relationship of $\dot{V}O_2$ to heart rate breaks down at higher work-loads when the heart rate frequently reaches its highest value before maximum oxygen uptake is achieved (Davies, 1968; Lindemann et al, 1973). This asymptotic nature of the heart rate/oxygen uptake relationship will therefore result in the underestimation of $\dot{V}O_2$ max should linear extrapolation procedures be employed. It is known that sub-maximal heart rate is affected by an increase in environmental temperature (Åstrand and Rodahl, 1977). However, since the analysis of variance revealed no significant difference between the temperature and humidity readings for the sub-maximal tests, the difference between the test results cannot be explained by a variation in the environmental conditions, although it is appreciated that body temperature, which was not measured in the present study, is a more important variable than environmental conditions.

Progressive Protocol

Very few studies have used protocols involving step intervals of 1 minute duration. Although Donald et al (1955) suggest that heart rate and oxygen uptake reach a steady state for certain work-loads within 1 minute Shephard (1967) has refuted this and instead declares that the assumption that steady state heart rates can be achieved in 1 minute can lead to serious errors (5-15% underestimate) in the prediction of $\dot{V}O_2$ max at higher work-loads. A closer inspection of the present results reveals that the heart rates for the progressive protocols were consistently lower than those for the identical work-loads using the steady state protocols. This almost certainly reflects a circulatory 'lag' in adjusting to the shorter incremental steps employed in the progressive tests and may well have compensated for the underestimation due to the asymptotic nature of the heart rate/oxygen uptake curve at higher work-loads, since the results for both progressive protocols reveal a non-significant difference between the predicted and measured $\dot{V}O_2$ max. These results suggest that for population studies both the cycle ergometer and step test could be employed successfully using the progressive protocol. For the individual, however, the error of prediction is considerable. The coefficient of variation for the cycle and step test was 13% and 16% respectively and would support Åstrand and Rodahl's (1977) assertion that most predictive tests have a S.D. of 10-15%.

Steady State Protocol

Maritz et al (1961) found that their method of fitting a straight line to the plot of four pairs of heart rate and oxygen uptake values produced a systematic underestimation of $\dot{V}O_2$ max of 6% (coefficient of variation 9%). They suggested that greater accuracy could be achieved if the line was fitted by the least squares method, which was the procedure used in the present study, although for some of the subjects the line was fitted using only three pairs of measurements. Wyndham (1968) noted that accurate predictions of $\dot{V}O_2$ max could be made using the Maritz procedure if the measurements were spread over a wide range of heart rates with the highest heart rate between 140-160 beats min^{-1}. The work-loads used in the present study produced final heart rates of between 133-160 and 126-161 beats min^{-1} for the cycle ergometer and step test respectively which may explain the closer approximation to the measured value for the cycle test (−9%) compared with the step test (−13%), although both differences were significant at the 0.01 level. Similar results have been recorded by other authors with underestimations ranging from 6-23% (Rowell et al, 1964; Shephard (1967); Davies (1968). Louhevaara et al (1980) actually found a slight overestimate of $\dot{V}O_2$ max using the Maritz extrapolation, although it should be noted that the criterion values were obtained using a cycle ergometer, which tends to reduce true $\dot{V}O_2$ max values by approximately 6% (Åstrand and Rodahl, 1977), while the sub-maximal $\dot{V}O_2$ was estimated from the work-load. The coefficients of variation, which for the studies mentioned ranged from 7-11%, correspond with the present findings of 9% and 13%.

In conclusion, it has been shown that $\dot{V}O_2$ max can be accurately predicted for a group of male subjects using the progressive protocol on either the cycle ergometer or stepping bench. The coefficient of variation for each of the procedures is approximately 14%, which suggests that individual predictions are liable to considerable error.

ACKNOWLEDGEMENTS

The author wishes to thank Syntex Research Centre for providing the laboratory facilities and Dr. R. Dow for assistance with the study, and Dr. G. C. Jefferson, Dr. N. C. C. Sharp and Dr. J. Thompson for their help in reviewing the manuscript.

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BOOK REVIEW

Title:	**RADIOLOGICAL DIAGNOSIS OF FRACTURES**			
Authors:	D. Findlay and M. Allen			
Publisher:	Bailleiere Tindall			
	Price: £15	Soft Cover	256 pages	Index

This is a book into which a huge amount of work has been put. There are extensive illustrations on 249 pages. One has to make a decision immediately as to whether this book is useful or not in that it shows a method of diagnosis based exclusively on line drawings, radiographs only being present on the first page or so. This reviewer finds this confusing because it is very difficult to ignore lines on a sheet of paper which can, as it were, be looked through on a radiograph. This, however, may represent a level of experience at which this book is not aimed but unfortunately its precise target has not been identified.

As in any book there are some omissions, incorrect labelling a muddle, that having been said, if you want to learn X-Rays from lines on paper this is probably the book from which to do it.

There is a great frustration in that there is no reference section, just by frequent references to named problems in the text.

The junior doctor may find this helpful in the context of fractures, but in my view will rapidly find study of the real X-Ray more helpful.

J. B. King

BOOK REVIEW

Title:	**1984 YEAR BOOK OF ORTHOPAEDICS**			
Editor:	D. Coventry			
Publisher:	Year Books per Blackwell, Oxford			
	Price: £45	Hard Cover	368 pages	Subject and Author Indices

This Year Book series provides a very useful introduction to a specialist subject. It, however, does presume a significant amount of knowledge on the part of the beholder, simply in that reviewers are not adequately introduced and on the whole are only well known to those intimately into this field.

The format is that papers are summarised with a brief review from one of the participating team at the end; out of necessity there has to be a selection of the papers. In this case, most of the reviewers seem to be from the same institution. Usually the Year Book represents a splendid attempt at an across the board presentation of what is new. There is little in this volume that is useful to those involved in Sports Medicine that will not have appeared in the Year Book of Sports Medicine itself.

J. B. King