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Critical power test for ramp exercise

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Abstract. The critical power test for cycle ergometry has been criticised as providing an overestimate of the real value of the critical power. Part of the blame may rest in the practical problem associated with getting reliable measurements of longer endurance times when power settings are not much above the critical power. However, by adjusting the incremental slope of ramp exercises, exhaustion brought about by high power and in a reasonably short time can be ensured, so avoiding this practical problem. This communication presents the theory and methods required to obtain estimates of both anaerobic work capacity and critical power from several ramp tests conducted to exhaustion. The method is illustrated with published laboratory data collected from exercising subjects.

Key words: Anaerobic work capacity – Cycle ergometry – Endurance – Incremental exercise – Regression

Introduction

The critical power (CP) test (Monod and Scherrer 1965; Moritani et al. 1981; Poole et al. 1988; Whipp et al. 1982) is actually a series of tests to exhaustion, each at different but fixed power settings on the cycle ergometer. The test is intended to provide estimates of two important parameters characterising work performance. Anaerobic work capacity (AWC, joules) has been described as that parameter representing the aggregate total work which can be performed by the limited fuel reserves of the body (phosphagens, glycolysis resulting in net lactate production, and O_2 stores), regardless of the rate at which these reserves are used (Poole et al. 1988). The critical power (watts) has been described as that power setting representing the upper limit for sustainable power (Poole et al. 1988); a power which could in theory allow indefinitely prolonged work. The CP has been shown to have important implications in the study of humans as a source of mechanical power (Wilkie 1960).

In its original formulation, Monod and Scherrer (1965) have postulated a linear relationship between the total work performed (W_{tot}) and the time to exhaustion at constant power (T, s):

$$W_{tot} = AWC + CP \cdot T \quad (1)$$

and experimental data have confirmed this model as an adequate description of the process. For constant power (P), Eq. 1 can be rewritten as

$$W_{tot} = P \cdot T = AWC + CP \cdot T$$

$$\text{i.e.} \quad P = AWC(1/T) + CP \quad (2a)$$

$$\text{or} \quad T = AWC/(P - CP) \quad (2b)$$

Equation 2b is the formulation often referred to as the (simple) hyperbolic model.

This general approach has also been adopted for running on the treadmill (Hughson et al. 1984), and for swimming (Biggerstaff and Hill 1992; Wakayoshi et al. 1992) to estimate an anaerobic 'distance' capacity and the critical 'velocity'. It could presumable be adopted also for rowing or other forms of dynamic exercise where workrate can be regulated.

Although the CP test has been regarded as providing a reliable measure of the maximal fatigueless rate of work (Gaesser and Wilson 1988; Nebelsick-Gullett et al. 1988) irrespective of which equation formulation is used (Smith and Hill 1992), it has more recently come under criticism. It is a recurrent finding that the experimentally determined CP seems obviously to overestimate the power which can be maintained continuously. Housh et al. (1989) have found that 11 out of 14 of their subjects could not maintain exercise on the cycle ergometer at their estimated CP, for 1 h. Average endurance was found to be 33.31 min. Jenkins and Quigley (1990) have found 6 out of 8 cyclists and McLellan and Cheung (1992) found 13 out of 14 subjects, unable to maintain CP for 30 min without exhaustion. In the former study (Jenkins and Quigley 1990), the subjects' mean attained power over 30 min was found to be 6.4% below their CP. A very similar conclusion has been reached by Pepper et al. (1992) for treadmill running at critical velocity. Average time to exhaustion was found to be even lower, at only 16.43 min. In two of these studies (Housh et al. 1989; Pepper et al. 1992), times to exhaustion at power settings above CP were accurately predicted, and the estimates of AWC were not called into question. However, evidence as to the test-retest reliability of AWC is ambiguous (Gaesser and Wilson 1988; Nebelsick-Gullett et al. 1988).

It is postulated that one reason for the inacccuracies of estimation of CP may lie in the fact that, in the interests of good experimental design, at least some tests ought to be performed at workrates only a little above CP. In such instances endurance times are long, and over these longer periods, factors such as motivation or other psychological variables may have a role in determining the onset of exhaustion. That is, the end point is greatly influenced by voluntary effort and is therefore not so well defined. The endurance data in such circumstances might for such reasons be inaccurate and/or lack precision. Indeed, all the studies quoted have not recorded data at long endurance times; some even suggesting otherwise. The constant power protocol may therefore not be the best test format to use when attempting to estimate CP. This suggests the necessity for a version of the test in which exhaustion is sure to occur in shorter times but which could be regarded as more reliable. That is, the relative error in endurance time is reduced. The ramp test on the cycle ergometer should satisfy this requirement, since exhaustion is precipitated much more by the high power reached than by the long time taken. It may also reduce or eliminate the overestimation bias inherent in the constant power test format.

Theory and methods

With the advent of computer-controlled cycle ergometers, it is now a simple matter to programme a ramp test to exhaustion at any given incremental slope (*S*; watts per second). In such a test, the time to exhaustion (T) can easily be recorded, and therefore with suitable choices for *S*, exhaustion should occur within times short enough to be regarded as reliable for any subject.

In this formulation of the CP test, starting from unloaded pedalling and referring to Fig. 1, power increases with time as a ramp with slope *S*, thus:

$$P = S \cdot t,$$

where t is the general time variable (s) and $0 < S < \infty$.

The W_{tot} performed is given by the triangular area under the power-time line, which can be evaluated as an integral:

$$\text{therefore } W_{tot} = \int_0^T P\,dt = S \cdot T^2/2$$

which can be expressed geometrically as:

$$= AWC + CP \cdot T - \tfrac{1}{2} CP^2/S$$

which holds provided $T > 0$.

This equation can be easily solved to yield:

$$T = CP/S + \sqrt{2AWC/S} \qquad (3)$$

which yields a model equation for the test data measurements relating time to exhaustion T in a ramp test of incremental slope *S*, to the parameters *CP* and *AWC*.

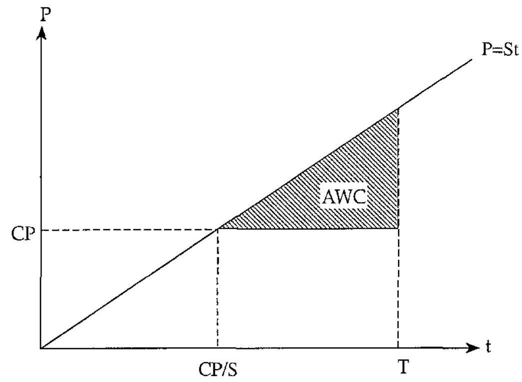

Fig. 1. Critical power (*CP*) test for ramp exercise – this figure gives a geometric representation to the derivation of Eq. 3 relating time to exhaustion (*T*) in a ramp test of incremental slope (*S*) to the parameters *CP* and anaerobic work capacity (*AWC*). This *straight line* shows the ramp increment in power (*P*) and *the area under the line* represents the work performed

Subjects would therefore perform a series of say four or five ramp tests to exhaustion on the cycle ergometer, each at a different slope S_i (i=1 ... 4 or 5). A range for *S*, depending on the subjects capability, of 0.25–1.50 $W \cdot s^{-1}$ is suggested, so as to attain exhaustion in times which are not unduly long. The corresponding time to exhaustion (T_i) would be measured in each case. These tests should be performed in random order, and with time intervals between each to allow for sufficient recovery to ensure the independence of successive tests.

The T_i would then be regressed against S_i, by fitting Eq. 3 to the data. This is a nonlinear equation, which can easily be fitted by nonlinear least squares using standard statistical software such as SigmaPlot (Jandel Scientific 1992, San Raphael, Calif.) so obtaining estimates of CP and AWC and their precision.

The extension of this procedure for running and swimming, using increasing velocity in place of ramp slope, is in theory quite obvious. It is recognised, however, that the practicalities do present some difficulties; for example, the transition from walking to running as velocity increases, and the lack of accurate control of velocity in the swimming pool (though perhaps less so in the swimming flume). A constant velocity running endurance test utilising increasing treadmill gradient has been reported by Hopkins et al. (1989), but an exponential model was utilised rather than the hyperbolic model of the CP test.

Illustrative example and discussion

The above procedures can be illustrated using the data published in Table 1 of Hansen et al. (1988). A group of 10 male subjects exercised to exhaustion on a cycle ergometer at three different ramp incremental slopes; 15, 30 and 60 $W \cdot min^{-1}$ incremented every 0.5 s. Duplicated tests were performed, in randomised order. Endurance times were recorded in seconds on each occasion. Equation 3 was fitted to each of these data sets using nonlinear least squares curve fitting, obtaining parameter estimates for CP and AWC (and standard errors) for each subject. The data and results of the fits are summarised in Table 1.

It is clear from Table 1 that Eq. 3 provides a good fit in all cases, even when R^2 is adjusted for degrees of freedom due to the small number of tests for each subject. Duplicated observations permit a lack of fit *F*-test

Table 1. Ramp exercise durations and details of the fit of Eq. 3

	Subject									
	1	2	3	4	5	6	7	8	9	10
Duration in seconds										
At 0.25 $W \cdot s^{-1}$	995	1040	1085	1030	930	—	1215	1185	874	715
	1035	970	910	970	875	835	—	1185	880	805
At 0.50 $W \cdot s^{-1}$	552	620	600	580	530	492	730	670	516	466
	555	617	635	510	505	460	695	695	535	455
At 1.00 $W \cdot s^{-1}$	302	350	330	310	298	285	408	375	300	304
	317	340	326	288	297	300	355	386	310	275
Parameter estimates										
CP (W)	203.8	142.8	150.1	199.3	152.2	128.1	214.3	204.2	127.4	91.2
SEE (W)	14.6	22.7	48.6	23.6	15.2	13.0	29.2	10.1	8.1	23.7
AWC (J)	4858	24235	20593	5178	11170	12721	17169	17247	17132	19475
SEE (J)	2202	8620	15080	2171	3939	3337	8721	3267	2608	8087
AT ($l \cdot min^{-1}$)	1.72	2.07	1.63	1.87	1.63	1.42	1.79	1.72	1.13	1.30
AT (W)	139.6	155.8	117.1	148.1	117.1	109.9	125.8	133.8	75.6	84.2
Goodness of fit										
R^2	0.9967	0.9906	0.9589	0.9912	0.9950	0.9962	0.9919	0.9987	0.9984	0.9804
$\overline{R}^2$	0.9959	0.9883	0.9486	0.9890	0.9938	0.9949	0.9892	0.9984	0.9978	0.9755
Lack of fit										
F-test	0.54	1.98	0.61	0.01	0.08	0.41	1.94	3.71	1 3.06	0.01

CP, Critical power; AWC, anaerobic work capacity; AT, anaerobic threshold
SEE, Standard error of the estimate

of Eq. 3. In no cases did this approach significance, even at the 10% level. In addition, Fig. 2 provides an illustration showing the best and worst fits (subjects 8, 3, respectively).

A comparative adequacy of the parameter estimates can be assessed by consulting Table 2, which compares estimates from various published studies. (All subjects are young adult men unless otherwise indicated).

It is clear from Table 2 that on average, the estimates of CP for the subjects in this study appear substantially less than those in other published studies, even to the extent of being more comparable to those for female subjects. The smallest *t*-statistic for comparisons with male data is highly significant (5.15, $P<0.001$), while for comparison with female data it is not (0.87, $P>0.1$). It is recognised that these observations are suggestive rather than definitive, but they appear to offer hope for correction of the overestimation bias evident in the standard test procedure for determination of CP.

The average of estimates for AWC for the subjects in this study is within the range spanned by these other studies; as are the standard deviation (SD) estimates for both CP and AWC, though the latter SD is somewhat higher than may be desired. In these latter respects, the CP test for ramp exercise appears to be equivalent to the standard test procedure.

The study of Hansen et al. (1988) has also recorded subject height, mass, anaerobic threshold (AT; both in terms of oxygen uptake and power) and maximal oxygen uptake. Neither lactate nor constant power data were collected on these subjects. Nevertheless, CP and

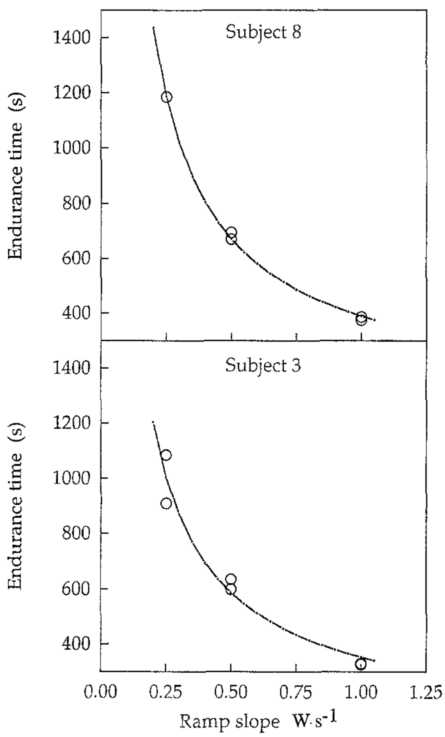

Fig. 2. Illustrative fits of Eq. 3 to data. The *upper and lower panels* illustrate the best and worst fits respectively of Eq. 3 to the data of Hansen et al. (1988). Subjects exercised to exhaustion in duplicated ramp tests on the cycle ergometer at incremental rates of 0.25, 0.50 and 1.00 $W \cdot s^{-1}$, incremented every 0.5 s

Table 2. Comparison of various parameter estimates of critical power (CP) and anaerobic work capacity (AWC)

Soruce	Subjects	CP (W)		AWC (J)		Notes
		mean	SD	mean	SD	
This study	10	161.2	41.7	14978	6412	
Gaesser and Wilson (1988)	11	211	30	14400	2580	Pretraining
	11	242	36	13400	4090	Posttraining
Housh et al. (1989)	14	197	39	14749	4642	
Jenkins and Quigley (1990)	8	314	27.9	18450	7277	Highly trained cyclists
McLellan and Cheung (1992)	14	265.1	39.3	—	—	7 trained, 7 untrained
Moritani et al. (1981)	8	203.9	36.5	13590	3844	
	8	144.5	20.9	8616	756	Women
Nebelsick-Gullett et al. (1988)	25	157	36	10083	2923	Women
Poole et al. (1988)	8	197	34	14600	4525	

AWC can be correlated with each other, and each of the available measurements for each subject. The CP correlated significantly only with AT in watts ($r=0.6741$, $P<0.05$) and AT in litres per minute ($r=0.6153$, $P<0.1$). The AWC did not correlate significantly with any of these measurements. Good correlates between CP and AT from ventilatory data have been previously reported (Moritani et al. 1981; Poole et al. 1988).

Conclusion

The ramp CP test protocol provides an alternative avenue for estimation of CP and AWC. It avoids potential inaccuracies inherent in constant power tests of long duration, and evidence suggests it may overcome the problem of overestimation of the CP inherent in the standard constant power test procedure. A full comparative study should be able to clarify this issue.

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