Original Research

The Critical Power Concept and Bench Press: Modeling 1RM and Repetitions to Failure

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ABSTRACT

International Journal of Exercise Science 7(2) : 152-160, 2014. Introduction: We demonstrate application of the 3-parameter critical power (CP) model derived for cycling and running, to performance at bench press exercise. We apply the model to both performance of a single repetition maximum (1RM) and multiple repetitions (reps) to failure at different sub-maximal weights. Methods: Sixteen weight-trained young adult male participants each performed a modified YMCA 1RM test and four sets of fixed cadence reps to failure at different sub-maximal weights. The CP model equation takes the form: n = ALC/(m – CL) + ALC/(CL – Lmax,), where n is the number of reps to failure and m is the sub-maximal weight lifted (kg). ALC is the anaerobic lift capacity (kg), CL is the critical lift (the maximal continuous aerobic ability at bench pressing, kg), and Lmax is the maximal 'instantaneous' lift (kg). Results: The 3-parameter critical power model fits recorded reps to failure very well in almost all subjects ($0.9556 < R2 < 0.9999$), and provides estimates of the three model parameters for each individual. CL was not significantly different from zero, suggesting that the aerobic energy contribution to short duration bench press sessions is negligible. When used to estimate 1RM for each subject, the CP model produces estimates significantly greater ($p < 0.05$) than those obtained using the YMCA procedure. Conclusion: The CP concept can be used to accurately model bench press reps to failure at different submaximal weights in a homogeneous group of individuals. Prediction of 1RM is possible, but caution should be exercised in interpreting and using the prediction.

KEY WORDS: Exhaustion, fatigue, resistance exercise, strength testing, task failure, weight lifting

INTRODUCTION

The original critical power (CP) concept (4, 8, 9) is a simple two component bioenergetic model of energy supply and work output. The model defines relationships between total work performed (Wtot), a constant power output (P) and endurance time (t). Specifically:

$$W_{tot} = AWC + CP.t \quad \text{and}$$
$$t = AWC/(P - CP)$$

Its two parameters are an anaerobic work capacity (AWC) representing the total work that can be performed by the body's anaerobic energy resources, and a critical power (CP) representing the upper limit for prolonged aerobic work. Both AWC and CP have important performance-related implications in the study of humans as a source of mechanical power (18). For ergometer exercise in which P can be set constant, application of the model is simple. For other exercise modalities (like running and swimming) velocity and distance are used as proxies for power and work respectively.

The 3-parameter CP model (10) is an extension of the 2-parameter model as a consequence of certain deficiencies. It introduces a feedback control system that modulates available maximal power above CP according to the extent to which the anaerobic capacity has been consumed. The hyperbolic nature of the model remains, and the relationship is expressed by the equation:

$$t = AWC/(P - CP) + k$$

where k = AWC/(CP – Pmax) is the negative time asymptote; Pmax being a theoretical finite upper limit to power output, interpreted as a maximum achievable 'instantaneous' power output.

The purpose of this study is to demonstrate the application of the CP concept to bench press exercise, use it to model lifting performance, estimate the model parameters, and to compare 1RM and other maximal lift parameters derived from this and other methods. We show in the next section how this equation can be sensibly applied to bench press exercise. The sections thereafter describe an experiment collecting bench press weight lifting data from sixteen participants; the fitting of an appropriate version of equation (1) to individual data for all participants; an examination of these fits; the use of the fitted equation to predict 1RM; and conclude with some practical remarks.

In almost all common continuous exercise modes, like running, cycling, Nordic ski-ing, and rowing, exercise is performed repetitively or cyclically with movements of the legs and/or arms. An individual repeatedly bench pressing a fixed weight up and lowering it down, is clearly performing similar cyclic continuous exercise.

At each cycle, the lifter performs physical work raising and lowering some mass m (kg) through a distance d (m) against the acceleration of gravity g ($m.s^{-2}$), and the raising and lowering process is performed repeatedly at some cadence c ($\#.min^{-1}$). The amount of work done in lifting the weight each minute is m.d.g.c joules and the corresponding power output is m.d.g.c/60 watts. The value of g is a constant, and for any individual d is fixed (related to arm length), so for fixed cadence c, power output is directly proportional to m, the mass lifted. Significant muscular effort (in fact the same force) is also required in the eccentric (lowering) phase of the bench press, despite that it may be perceived as easier. Nevertheless, as with lifting, g, d, and c are constant, and so the power component during the lowering phase depends also only on the mass lifted, m. Endurance time t for continuous exercise is usually measured in seconds (s). If the weightlifter manages n lift repetitions (reps) at cadence c until exhaustion, then the endurance time is 60n/c seconds. So with c again fixed, endurance is directly proportional to n. Thus in the above equation we can use the mass lifted, m kg, and the number of reps, n, to exhaustion as proxies for P and t respectively. Likewise the product m.n (total weight cycled) can be used as a proxy for the total work performed, W_{tot}.

Thus, applying equation (1) for any individual bench pressing m kg repeatedly at fixed cadence, the number of lifts n until exhaustion can respectively be given by:

$$n = ALC/(m - CL) + k$$

In this equations ALC (anaerobic lift capacity, kg) is the total lifting capacity equivalent of the anaerobic energy stores; CL (critical lift, kg) is the vertical asymptote to the hyperbolic curve, representing a weight which in theory could be bench pressed indefinitely often at that cadence; and k (#) is the negative horizontal asymptote to the hyperbolic curve. In many cases it is more meaningful to reparameterise equation (2) replacing k by $ALC/(CL - L_{max})$ where $L_{max} = CL - ALC/k$ (kg) is the point at which the hyperbola intersects the horizontal axis. This value represents an upper bound to the mass that the subject is able to lift at all, beyond which his muscular strength would be insufficient to move it; being interpretable as a theoretical maximal 'instantaneous' life (10).

In this application we are interested in fitting a model linking reps to failure to sub-maximal weight lifted, and in estimating 1RM, achievable by solving equation (2) when n = 1. The bench press is selected for illustrative purposes because it is a common, well-known and simple resistance exercise procedure. To obtain estimates of ALC, CL and k (or L_{max}) and hence 1RM for any individual, we need data from a series of suitably conducted weightlifting trials to task failure. The question as to which of the 2- or 3-parameter equations should be used will be addressed below.

METHODS

Participants

Sixteen healthy, physically active and weight-trained male volunteers (age 21.7 + 0.5 yr; height 180.2 + 6.4 cm; weight 87.0 + 9.9 kg) participated after being informed of the risks and benefits of the study. Recruitment was in response to an advertisement at the Weight Room of the Student Recreation Centre and by word of mouth. The University Human Ethics Committee granted approval, and all participants signed informed consent. To be classified as weight-trained, an individual had to be currently involved in moderate to heavy free-weight training dating back no less than ten weeks from the start of the study. In addition weight-trained participants were required to have trained their anterior deltoids and pectoralis major muscles under a repetitive bench press protocol at least once per week during at least this ten-week period.

Subjects attended testing sessions on five different days. At the first session each participant performed a YMCA 1RM bench press test as described below. On each of the subsequent four testing days subjects performed repetitive bench pressing to task failure at one of four different sub-maximal weights, in counterbalanced order. All subjects used the same weight equipment and were instructed and supervised to ensure standardization of the correct safe lifting techniques.

Protocol

The 1RM testing session for each subject followed the modified YMCA procedure described by Kim et al. (6), from an initial weight known by each subject as being close to their 1RM. Three minutes rest were allowed between each trial set (17).

The remaining four sessions were performed with a spread of sub-maximal weights subjectively chosen according to each subject's knowledge of their own lifting abilities so as to allow between a minimum of 3-10 repetitions for the heaviest weight, 10-20 for the next heaviest, 21-40 for the next, and a maximum of at least 41 repetitions for the lightest weight. For the most prolonged of these sessions weights were selected such that individuals would not be expected to endure lifting much longer than two to three minutes. This is regarded as a much shorter time than normally recommended for application of the 2-parameter form of the model (4, 10). This selection of weights and repetitions was deliberately chosen to bias data towards the brief end of the time scale, which benefits the accurate estimation of 1RM rather than of CL.

The selection of an appropriate cadence c is not arbitrary. It should not be too low otherwise lifting sessions may tend to be of rather longer duration than suitable for estimation of 1RM; Brzycki (2) regards sessions of more than 10 repetitions as unsuitable for 1RM prediction. Furthermore very low cadences introduce an intermittent character to the exercise, where the application of the CP model is significantly more complex than for continuous exercise (12). Similarly, cadence should not be too rapid either. This restriction represents the necessity to prevent subjects literally dropping the weight as fast as they could and using their anterio-stretch reflex as an aid to pressing more repetitions of a given weight than would otherwise be the case. Cadence selection is also relevant to cycling, where crank rpm are typically held constant within the testing protocol. The reason for this is that muscle forces differ when stretch/shortening cycles are faster or slower, though this complication cannot be eliminated when running because stride frequency normally changes with running velocity.

At each commencement, the selected weight was placed into the subject's hands with arms at full extension. The weight was repeatedly lowered and pressed upwards to full extension at a cadence of 20 repetitions per minute by adherence to a metronome. This cadence was selected as a result of pilot trials seeking a compromise between being too fast or too slow as discussed previously. Task failure was deemed to have occurred once the subject could no longer press the weight to full extension at the required cadence. The number of successful repetitions was counted in each case. Warm-ups were performed before commencement of each trial in accordance with association standards (14). As a means of eliminating carry-over or order effects, the order of each four trials was counterbalanced such that each set was performed an equal number of times as the first, second, third and fourth trial over the sixteen subjects. At least 24 hours were allowed between each testing session, as this is regarded as sufficient time to allow for reproducibility of maximal lifting effort (15).

Also, since a variety of methods are used to estimate 1RM, for the purposes of comparison the Brzycki (2) method of estimating 1RM was applied to the results from that session in which the highest weight and least number of repetitions were recorded for each subject.

Statistical Analysis

Results are summarised as means with standard deviations. Curve fitting utilised SigmaPlot software (Jandel Scientific, San Rafael, CA). Goodness of fit was assessed using the coefficient of determination, R^2. Measures of maximal lifting ability for all participants were examined using a repeat measures analysis of variance. Significance was accepted for p-values less than 0.05.

RESULTS

The following table summarises the lifting performances of all sixteen participants (means + SD).

Table 1. Bench press performance summary.

Variable	41+ reps	21-40 reps	11-20 reps	3-10 reps	1RM
Lift: kg	32.6 ± 14.3	47.9 ± 18.9	65.3 ± 21.4	80.6 ± 22.9	94.7 ± 17.6
# reps	47.5 ± 14.4	26.7 ± 7.5	13.5 ± 3.8	5.7 ± 2.1	1

When plotting and examining the data (total weight lifted versus number of reps to failure) from any one participant it is apparent that a straight line is not an acceptable representation. For example, Figure 1 below plots W_{tot} as a function of n the number of reps for participant 16. Its curvilinear shape is quite typical of all subjects. For this reason, and as mentioned above, together with those described in the original formulation of the 3-parameter model (9), the 2-parameter model is abandoned in favor of the 3-parameter version.

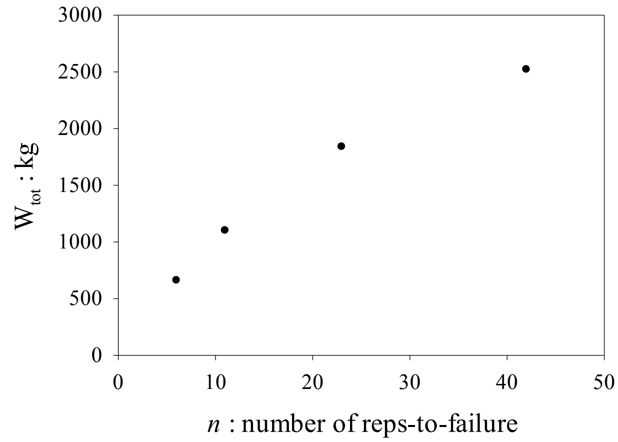

Figure 1. W_{tot} vs n for participant # 16

Equation (2) was therefore fitted to the data from each of the sixteen participants. Based on the model theory, the following parameter constraints were applied for all fits: ALC > 0, CL > 0 and k < 0. Table 2 summarizes the results of these fits.

Table 2. Individual fits of equation (2) to bench press lifting repetitions to failure

Subj #	*ALC* kg	*CL* kg	*k*	R^2	L_{max} kg	1RM kg	1RM* kg	1RM+ kg
1	1880	0.0	-14.88	0.9965	126.3	118.4	95.0	98.7
2	1570	0.0	-12.89	0.9556	121.8	113.0	75.0	76.4
3	952	8.8	- 8.32	0.9847	123.3	111.0	82.5	81.8
4	1063	0.0	-17.12	0.7930	62.1	58.7	55.0	56.3
5	841	0.0	- 4.36	0.6698	192.9	156.9	85.0	81.3
6	1868	0.8	-12.41	0.9885	151.3	140.0	95.0	109.3
7	1879	0.0	-13.93	0.9835	134.9	125.9	97.5	95.6
8	1908	0.0	-14.04	0.9863	135.9	126.9	95.0	98.7
9	2651	0.0	-22.11	0.9877	119.9	110.8	95.0	102.9
10	2980	15.4	-23.88	0.9996	140.2	135.2	125.0	132.0
11	2819	0.0	-26.35	0.9915	107.0	103.1	90.0	96.0
12	1211	8.6	-11.00	0.9932	118.7	109.5	87.5	90.0
13	2790	0.0	-25.30	0.9975	110.3	106.1	95.0	99.3
14	2717	0.0	-21.00	0.9893	129.4	123.5	112.5	109.1
15	3142	0.0	-26.56	0.9862	118.3	114.0	102.5	102.9
16	4676	0.0	-35.78	0.9999	130.7	127.1	127.5	127.8
Mean	2184	2.1	-18.12	0.9564	126.4	117.5	94.7	97.4
SD	1010	4.6	8.17	0.0912	26.3	21.0	17.6	18.6

* Using the YMCA method of estimation (6)
+ Using the Brzycki method of estimation (2)

Apart from two moderately good fits (R^2 = 0.6698 and 0.7930), 14 of the 16 cases yielded very good fits (R^2 > 0.9556) of equation (2). This evidences the acceptability of the 3-parameter critical power model as a good representation of the bioenergetics of bench press exercise. Indeed the critical power model appears to adequately describe the bioenergetics of a wide variety of exercise modalities (5, 11, 13).

Table 2 also includes the estimated values of Lmax (calculated from the ALC, CL and k estimates), and 1RM for all 16 participants, together with their 1RM measures described previously. One feature within Table 2 is that for 12 participants, CL is estimated specifically as zero. In three of the four other cases the estimates are small and not significantly greater than zero ($p > 0.05$). Elsewhere in the table, the estimates are consistent with the participant's own observed abilities.

The four differently derived measures of maximal lifting ability for all participants presented in Table 2 were examined using repeated measures analysis of variance. This examination indicates statistically significant differences between subjects ($p < 0.001$) and between measures of maximal ability ($p < 0.001$). To more specifically examine the latter differences, the following three independent post-hoc sub-hypotheses were tested using the method of orthogonal contrasts:

a) L_{max} = average of all 1RM measures (1-tail alternate, >)

b) Modelled 1RM = average of YMCA and Brzycki measures (2-tail alternate)

c) YMCA measure = Brzycki measure (2-tail alternate).

This more detailed examination rejects sub-hypotheses a) and b); revealing that L_{max} is significantly higher than the average of the three 1RM estimates and that 1RM estimated from the 3-parameter CP model is significantly higher than the average of the two other 1RM estimates. On the other hand, it accepts sub-hypothesis c) that the YMCA and Brzycki methods produce equivalent 1RM estimates.

DISCUSSION

This is the first time the critical power model has been applied to bench press exercise. Observing that the model fitting is successful extends applicability of the critical power model beyond those exercise modalities where it is commonly employed; cycling, running, swimming and kayaking. Nevertheless, we regard this study as a first step. Its main limitations are that the sample size is small; that the all-male set of participants were quite homogeneous in age, fitness level, etc.; and that a single fixed cadence was used.

It is not unexpected that L_{max} is significantly greater than the 1RM estimates as it is a fundamentally different type of attribute, representing a theoretical maximal 'instantaneous' effort. Likewise it would be expected that the YMCA and Brzycki 1RM estimates would not differ significantly. However it is noted that the modeled 1RM estimate was significantly higher than the other two. While not explaining this observation explicitly, we note the remark of Brzycki (2) that the relationship between the number of reps to task failure and percentage of maximum load was not exactly linear. That non-linearity concern was at the higher end, and so restricted application of his method to instances where the maximum number of reps-to-fatigue was no more than 10. It is likely also the case that a non-linearity concern is present at the lower end. Note in passing that the 3-parameter model equation (2), though strictly not comparable to the Brzycki equation, is non-linear. Philosophically, note also that all these are estimates of an almost unattainable attribute and as such there is no real standard against which to compare all the various estimates. It may be that despite the similarity of the YMCA and Brzycki estimates, both are negatively biased. Equally, the 3-parameter model estimate may itself be positively biased. The resolution of this dilemma is not obvious.

Of note was the observation that most of the CL estimates were zero; because the non-negativity constraint was invoked by the curve fitting software. In fact taken as a group, analysis indicates that CL is not significantly greater than zero ($p = 0.3271$). This is not the case in all applications of the CP model we reference, and we have not been able to establish whether any zero values of this parameter have ever been reported. This suggests that the aerobic component of these exercises is negligible. There may be at least five factors to consider when interpreting this finding.

Firstly, none of the lifting sessions lasted longer than a few minutes, suggesting there may be a design artefact present, in the sense that no data for longer lasting lower weight sessions were collected. Had this been the case, with sessions of many more lifts been incorporated, the CL estimates may well have been greater than zero. Bench press sessions of extended duration are very rare, and differing durations of test sessions have been shown to affect the parameter estimates (1). Secondly, such short lasting sessions as were employed would, by the very nature of oxygen uptake kinetics, have had little aerobic component anyway. That is, they were simply not long enough for oxygen uptake to reach anywhere near a steady state level above rest. Thirdly, all subjects were observed to be holding their breaths for most of the sessions, which naturally diminishes any aerobic contribution. Such occurrences were not specifically recorded at any lifting sessions, nor necessarily observed at all of them. In view of this, researchers conducting similar lifting protocols in the future may be advised to specifically record details of any such occurrences. Fourthly, the arm muscles are in a continuous state of activity throughout the entire lifting/lowering cycle (concentrically, eccentrically, and isometrically). The intramuscular pressure that this generates would likely hamper blood flow and consequently limit any aerobic contribution to the exercising muscle. Finally, it may nevertheless be the case that $CL = 0$ is a genuine phenomenon for this type of exercise, which has not been previously empirically reported. If this can be verified in studies specifically designed to investigate its occurrence, then a less tentative interpretation should be possible.

There appears to be no definitive data on choice of suitable cadence for this type of exercise. The three seconds per rep choice of cadence in this study was based on the rationale presented above. Nevertheless some researchers have suggested slower cadences. Brzycki (3) recommends 6 seconds per rep to maximize muscular work during a set, while Westcott et al. (16), advocates as much as fifteen. Thus, future research should explore the use of differing cadences when testing the model.

The primary conclusion of this study is that the 3-parameter version of the CP model can be utilized successfully to model repetitions to failure in bench press exercise. More broadly, it provides estimates of aerobic and anaerobic lifting parameters (CL and ALC respectively) and of an upper bound to the lifting ability of any individual (L_{max}). In particular it appears that in this application of the CP model, the aerobic energy supply component to short duration lifting sessions, as expressed through the CL, may be negligible.

In addition this modelling process can provide predictions of the number of reps-to-failure for any given weight for any individual; 1RM in particular, which is used to assess strength levels in order to evaluate current training and formulate new training programs (7). In this study such estimates are limited to weights associated with generating numbers of reps-to-failure below about 50, or lifting sessions lasting no longer than about three minutes. The estimates of 1RM obtained in this way appear to be higher than those obtained by more traditional means. It is arguable that the 'true' 1RM lift for any individual is not a directly measurable attribute, only estimable by various means. Thus it cannot unequivocally be determined which of the various estimates described in this paper is closest to the 'true' value in any sense. These are matters of opinion.

Consequently, there are several practical implications for athletes, their coaches, and sport scientists that can be deduced from this study:

- The numbers of bench press repetitions to failure at submaximal levels can be successfully predicted using the 3-parameter critical power model

- The 1RM bench press value of the lifter can be accurately estimated using this model

- Aerobic, anaerobic and maximal parameters describing these abilities of the lifter can also be estimated using this model

The bench press was selected for illustrative purposes only, because it is a common, well-known and simple resistance exercise procedure. This should not be taken to imply that the model is considered inappropriate for other lift types. As a consequence of the work reported above, we believe the model would in fact also fit other lift types.

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