STRENGTH TRAINING INCREASES ENDURANCE TIME TO EXHAUSTION DURING HIGH-INTENSITY EXERCISE DESPITE NO CHANGE IN CRITICAL POWER

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ABSTRACT
Sawyer, BJ, Stokes, DG, Womack, CJ, Morton, RH, Weltman, A, and Gaesser, GA. Strength training increases endurance time to exhaustion during high-intensity exercise despite no change in critical power. J Strength Cond Res 28(3): 601–609, 2014—The purpose of this study was to determine whether improvements in endurance exercise performance elicited by strength training were accurately reflected by changes in parameters of the power-duration hyperbola for high-intensity exercise. Before and after 8 weeks of strength training (N = 14) or no exercise, control (N = 5), 19 males (age: 20.6 ± 2.0 years; weight: 78.2 ± 15.9 kg) performed a maximal incremental exercise test on a cycle ergometer and also cycled to exhaustion during 4 constant-power exercise bouts. Critical power (CP) and anaerobic work capacity (W') were estimated using nonlinear and linear models. Subjects in the strength training group improved significantly more than controls (p < 0.05) for strength (~30%), power at V0peak (7.9%), and time to exhaustion (TTE) for all 4 constant-power tests (~39%). Contrary to our hypothesis, CP did not change significantly after strength training (p > 0.05 for all models). Strength training improved W' (mean range of improvement = +5.8 to +10.0 kJ; p < 0.05) for both linear models. Increases in W' were consistently positively correlated with improvements in TTE, whereas changes in CP were not. Our findings indicate that strength training alters the power-duration hyperbola such that W' is enhanced without any improvement in CP. Consequently, CP may not be robust enough to track changes in endurance capacity elicited by strength training, and we do not recommend it to be used for this purpose. Conversely, W' may be the better indicator of improvement in endurance performance elicited by strength training.

KEY WORDS resistance training, anaerobic work capacity, severe-intensity exercise

INTRODUCTION
The key factor in endurance performance is the ability to maintain the highest possible power output (during cycling), velocity (during running), or other appropriate analog of power depending on the sport (e.g., swimming or rowing) for a sustained period of time (3). This maximum sustained exercise intensity is known as the maximum steady state and can be approximated by measurement of critical power (CP) (29,33). Critical power represents the power asymptote of the hyperbolic relationship between power output and endurance time, and CP demarcates the heavy and severe-intensity exercise domains (14,21) (Figure 1 for a depiction of CP and exercise intensity domains). The curvature constant of the power duration hyperbola (W') represents a fixed amount of work that can be performed above CP and is thought to reflect energy derived from substrate-level phosphorylation via nonoxidative glycogenolysis and creatine phosphate stores and additional myoglobin-bound and venous hemoglobin-bound O2 stores (15,21,32).

Critical power is considered an important aerobic parameter in predicting endurance performance (19,29,30) and may be useful for monitoring performance in endurance sports (43). The concept of CP is applicable to all endurance sports (43) and has been modified for application to intermittent sports (29) such as soccer, rugby, and hockey. For example, CP testing has been used to assess performance in collegiate rowing athletes (23,24), to determine optimal rest periods between interval exercise training bouts in collegiate rugby and hockey athletes (11), to track training-induced changes in swimming performance in Olympic and club level swimmers (34,39), and to assess feasibility as an alternative to standard military physical fitness testing (12). Furthermore, CP and W' have been used to prescribe and determine the effects...
of various exercise training programs (15,20,34,39,41), examine mechanisms of fatigue (26,27,29,32,33,42), and evaluate the effectiveness of nutritional supplements (10,26,37). Although the effects of aerobic training (15,20,34,39,41) and dietary supplementation (10,26,37) on CP and $W^\prime$ have been explored, strength training interventions have not been thoroughly investigated.

Various types of strength training have been shown to significantly improve long-term (2,18,25) and short-term (17,18,38) endurance performance. These improvements in endurance performance are unrelated to changes in peak aerobic capacity (VO$_{2\text{peak}}$) and are most likely due to increases in exercise economy, muscular strength, and improved anaerobic power and work capacity (1,5,22,35,45). As a result, incorporation of strength training into endurance athletes' training regimens has become quite common (1,22). Because CP is determined on the basis of exercise time to exhaustion during high-intensity constant-power exercise bouts (21), the results of previous studies mentioned above (2,17,18,25,38) would predict that CP should be increased with strength training.

The only study that has explored the effects of strength training on CP reported that 6 weeks of strength training in young men increased $W^\prime$, but did not increase CP despite significant increases in leg strength (4). An increase in $W^\prime$ after strength training would be expected. However, it is not readily apparent why CP would not improve after a strength training program that improved leg strength by as much as that reported in other studies that also demonstrated significant increases in short-term (17,18,38) and long-term (2,18,25) endurance. Other studies that have examined the effects of interventions on CP and $W^\prime$ have shown an inverse relationship between the changes in the 2 parameters (4,15,20,41,42).

Short-term aerobic exercise interventions would be expected to increase CP and elicit no change in $W^\prime$ (15,20), whereas creatine supplementation would be expected to increase $W^\prime$ and have no effect on CP (10,26,37). Conversely, 3 of the studies using the interventions mentioned above reported moderate-to-high inverse relationships between the changes in $W^\prime$ and CP (15,20,41). These relationships may be due to shortcomings of CP modeling and not to actual decreases in CP or $W^\prime$. Because strength training improves both anaerobic power and endurance performance, this inverse relationship would not be expected in response to strength training. Because CP testing is used to evaluate the effects of interventions on athletic performance (10–12,23,24,34,39), and the 1 published report of the effects of strength training on CP produced an equivocal finding (4), we felt that it would be of value to clarify the effects of strength training on CP and $W^\prime$.

Therefore, the purpose of this study was to evaluate the adequacy of CP modeling to produce estimates of CP and $W^\prime$ that reflect improvements in high-intensity exercise tolerance after strength training. Such information may enhance the application of the CP concept to endurance sports, particularly when strength training is used to improve performance (43). Because both linear and nonlinear models are commonly used to estimate CP and $W^\prime$ (21), we extended the previous work by Bishop and Jenkins (4) to include both linear and nonlinear models, more time points for parameter estimation, and a longer training program. We hypothesized that changes in both CP and $W^\prime$ would reflect expected increases in endurance exercise performance in the severe-intensity domain after strength training.

**METHODS**

**Experimental Approach to Problem**

We conducted a randomized controlled strength training intervention to elicit increases in strength that would be sufficient to significantly increase tolerance for exercise in the severe-intensity domain. The control group was necessary to show that no changes occurred with our independent variables due to time alone. We chose training group (strength or control) as our independent variable and CP as our primary dependent variable. Secondary dependent variables included strength measurements, time to exhaustion for each constant power bout, $W^\prime$, peak power (PP) achieved during the incremental exercise test, and VO$_{2\text{peak}}$. Therefore, if strength and time to

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**Figure 1.** A) The hyperbolic relationship between time to exhaustion and power output. The dashed line represents critical power (CP) and $W^\prime$ is represented by the hyperbolic line. B) The relationship between time and oxygen uptake for 3 different work rates (1 in each domain). The moderate-intensity domain encompasses exercise intensities below the lactate threshold and is characterized by achievement of steady state oxygen uptake and metabolic homeostasis within 3–5 minutes. The heavy-intensity domain includes intensities at or above the lactate threshold but below maximal lactate steady state (i.e., CP) and is characterized by delayed achievement of steady state. The severe-intensity domain includes intensities above CP, where oxygen uptake does not attain a steady state and may eventually reach its maximum. Within the severe-intensity domain, $W^\prime$ contributes significantly to the energy demands of exercise and, theoretically, would be depleted at the point of fatigue.
exhaustion (TTE) were improved in the strength training group and no changes occurred in the control group, then the stimulus was adequate to test our research question.

All subjects underwent 6 separate days of preintervention and postintervention testing including: (a) A VO2peak test to determine aerobic power; (b) 4 separate days of constant-power cycle ergometer exercise bouts to exhaustion (to determine TTE at each power output, CP, and Hr’); and (c) Strength testing to assess changes in strength. All testing visits were conducted in the Fall, during the same general time of day for each subject (e.g., 8–11 AM, 12–3 PM, or 4–7 PM), and while subjects were approximately 2 hours postabsorptive. We used unequal randomization, a well-documented procedure for reducing investigator and subject burden while maintaining adequate statistical power (8). Other than the strength training program, subjects were asked to maintain their habitual physical activity level and not change their diet during the 8-week period.

Subjects
The study was approved by the Human Investigation Committee at the University of Virginia. Each subject was informed of all the risks associated with participation in the study and gave written and informed consent to participate. Results of the a priori power calculations based on our previous data (15) showed that 5 subjects in each group would yield 90% power to detect a 10% difference in CP between groups. To ensure adequate statistical power in case the changes we observed in CP were less than 10%, we enrolled 21 healthy recreationally active young males who were not currently engaged and had not been engaged in strength or endurance training for at least 1 year. All subjects engaged in less than 2 d·wk−1 of endurance exercise and were not engaged in any form of resistance exercise. Subjects were randomized into the strength training or control groups using a 2:1 ratio. Therefore 7 subjects were assigned to the control group and 14 were assigned to the strength training group. Nineteen participants (mean ± SD: age: 20.6 ± 20.6 years; weight: 78.2 ± 15.9 kg) completed the study. Two subjects in the control group did not return for follow-up testing, therefore, the final number of subjects in the control group was 5.

Procedures
Strength Training. Subjects in the strength training group performed strength training 3 times per week for 8 weeks. Each subject performed the following exercises in the following order with 90–120 seconds of rest between sets (lower extremity followed by upper extremity, largest muscle groups to smallest): parallel squat, seated knee extension, prone knee flexion, standing heel raise, bench press, military press, elbow extension, and elbow flexion. Three sets at a weight equivalent to an 8 repetition maximum (RM) were performed each workout for all exercises except heel raises in which 3 sets at a 12RM was used. Weight was adjusted continuously to accommodate strength gains throughout the study. Although this was not a typical periodized resistance training program, we modeled our program after other investigators who reported significant increases in endurance performance, sufficient to allow us to test our hypothesis (2,18,25).

Strength Testing. Strength was determined using a 1RM test for each of the exercises listed above in the same order as above. Before each test, subjects warmed up by completing 10 repetitions with −50% of their perceived 1RM followed by a 3–4 minutes rest period before the testing began. Next, subjects attempted their first lift at −5–10% below their perceived 1RM. Weight was increased in 5–10 pound increments until the subjects could not complete the lift. After a failed attempt, subjects were allowed to attempt the lift 1 more time. Four minutes of recovery were given between each successful or failed lift. The highest weight successfully lifted was recorded as 1RM. The testing protocol was designed to find 1RM in 3–5 attempts. Preintervention testing for the strength training group occurred after the first 3 workouts to familiarize subjects with the lifting techniques. One repetition maximum testing was conducted again after the 8-week intervention period to determine changes in strength in both groups.

Determination of VO2peak. Before and after the 8 weeks of strength training or control period, subjects performed an incremental exercise test on a friction-braked cycle ergometer (Monark, Sweden) to determine VO2peak. Throughout the test, subjects were instructed to maintain pedaling cadence at 60 revolutions per minute (rpm) with the assistance of a calibrated metronome. Cadence and load setting on the ergometer were continuously monitored by a laboratory technician. The test started with 2 minutes of unloaded cycling followed by an increase in power to 30 W for 1 minute. Thereafter, power output was increased by 15 W every 3 minutes until volitional exhaustion. Subjects were given strong verbal encouragement to maintain the desired cadence. The highest power achieved during this incremental test was used as a reference point for selection of power outputs to be used during subsequent constant-power exercise bouts to exhaustion (7,13). Pulmonary ventilation and gas exchange were continuously measured as previously described using a calibrated dry gas meter (Rayfield RAM-9200, Waitsfield, VT, USA) fitted with a potentiometer, 7-L mixing chamber, and Applied Electrochemistry S-3A oxygen analyzer (AEI Technologies, Applied Electrochemistry, Pittsburgh, PA, USA) and Beckman LB-2 carbon dioxide analyzer (Beckman, Schiller Park, IL, USA) (36,44). VO2peak was taken as the highest 15-second value reached during the test.

Determination of the Power-Duration Relationship. The power-duration relationship was determined both before and after the 8-week training or control period. Four constant-power outputs were selected as described previously (7,13) and were designed to produce exercise TTE in the range of [603]
1–20 minutes. Subjects completed these 4 tests in random order on separate days. Each test was separated by at least 24 hours. After a warm up on the same cycle ergometer used for the V <sub>peak</sub> test, subjects pedaled to exhaustion at a cadence of 60 rpm. Pedaling frequency was achieved by having subjects pedal to a calibrated metronome while having cadence monitored by a technician. The load setting on the ergometer was continuously monitored and adjusted, as needed, to keep output constant (13). Exhaustion was defined as the point at which the subject could no longer maintain the pedaling cadence of 60 rpm. When cadence fell below 60 rpm, the subject was given verbal encouragement to pedal faster. If the subject could not return to 60 rpm, the test was terminated and TTE recorded to the nearest second. At no time was the subject provided information about the elapsed time or power output of the test. Using data from our previously published work (15), we demonstrated, using Cronbach’s alpha, good test-retest reliability for the estimation of both CP (intraclass correlation coefficient [ICC] = 0.977) and W′ (ICC = 0.879).

### Mathematical Modeling

As described previously (13), we used the following models to produce parameter estimates of the power-duration relationship:

- **Linear** \( W = W' + (CP \times t) \) \[1\]
- **Linear** \( P = (W'/t) + CP \) \[2\]
- **Nonlinear** \( t = W'/ (P - CP) \) \[3\]

where \( P = power, t = TTE, W = work (Pt), W' \) represents the curvature constant of the power-duration hyperbola, and CP represents the highest sustainable aerobic power output. These 3 models were used because they all have been used in previous studies and, although mathematically equivalent, may produce different estimates of CP and W′ (15).

### Statistical Analyses

Statistical analysis was performed on SPSS statistics 20 (IBM, Armonk, NY, USA) using 2-way repeated measures analysis of variance to compare pretraining and posttraining measurements of our dependent variables CP, W′, TTE, V<sub>peak</sub>, PP, and 1RM strength measurements between groups. The parameter estimates were derived using least squares regression in SigmaPlot (Jandel Scientific, San Rafael, CA, USA). Pearson’s correlations were used to check goodness of fit for each model, to assess the strength of relationship between changes in TTE and both CP and W′, and to determine whether changes in CP and W′ were correlated. Linear mixed models in SPSS with subjects as the random factor and model as the fixed factor were used to compare CP and W′ values estimated by different modeling techniques. Bonferroni post hoc tests were used to find which parameter estimate differed from the others. All dependent variables were checked for normality using the Shapiro-Wilk test. An alpha level of \( p < 0.05 \) was considered statistically significant.

### Table 1: Preintervention and postintervention 1RM strength measures (kg).

<table>
<thead>
<tr>
<th>Strength training group, N = 14</th>
<th>Control group, N = 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>Squat</td>
<td>112.9 ± 27.3</td>
</tr>
<tr>
<td>Knee extension</td>
<td>71.3 ± 19.9</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>25.9 ± 8.1</td>
</tr>
<tr>
<td>Lat pulldown</td>
<td>72.7 ± 17.6</td>
</tr>
<tr>
<td>Bench press</td>
<td>83.8 ± 23.9</td>
</tr>
<tr>
<td>Military press</td>
<td>52.3 ± 14.0</td>
</tr>
<tr>
<td>Elbow extension</td>
<td>38.1 ± 10.8</td>
</tr>
<tr>
<td>Elbow flexion</td>
<td>33.9 ± 8.8</td>
</tr>
</tbody>
</table>

*Values represent mean ± SD.
†Significant group × time interaction, \( p < 0.05 \).
1RM = one repetition maximum.
RESULTS

The results of the Shapiro-Wilk tests showed that all dependent variables were normally distributed, therefore meeting the assumptions of the parametric statistics used. Table 1 shows the changes in strength measurements that occurred after the 8-week intervention period. Subjects in the strength training group showed significant improvements with each lift, whereas subjects in the control group showed no changes. Mean improvements in the strength training group in lower body strength were 21% with squat...
and knee extension and 39% for knee flexion. Upper body strength gains ranged from 14% for bench press to 20% for elbow flexion.

Although $V_{O2}$peak was not changed after strength training (3.40 ± 0.60 L·min⁻¹ vs. 3.40 ± 0.50 L·min⁻¹), PP achieved during the incremental maximal exercise test was increased significantly (213 ± 29 W vs. 230 ± 27 W; $p < 0.05$). The control group showed no significant changes in $V_{O2}$peak or PP. Subjects in the strength training group increased TTE during all 4 constant-power bouts ($P_1$ = highest power output; $P_4$ = lowest power output) significantly more than the control group after the intervention period ($P_1$: +47% vs. +7%; $p < 0.010$; $P_2$: +36% vs. +1%; $p = 0.013$; $P_3$: +50% vs. +2%; $p = 0.041$; $P_4$: +24% vs. −5%; $p = 0.008$; Figure 2).

Parameter estimates (mean ± SD), standard error of estimate (SEE), and goodness of fit values for each of the CP models in both groups are shown in Table 2. All equations produced excellent goodness of fit. Critical power estimates for the 3 models differed significantly from each other ($p = 0.011$). Bonferroni post hoc results showed that the linear (P) model yielded significantly higher CP values compared with the nonlinear model ($p = 0.008$). Likewise, $W'$ estimates differed significantly from each other ($p < 0.001$). Post hoc results showed that the linear (P) model yielded significantly lower $W'$ results than the nonlinear model ($p = 0.042$). The CP estimate using the nonlinear model tended to decrease after the intervention period in the subjects overall ($p = 0.053$, Figure 3A and Table 2), but there was no significant difference between groups ($p = 0.606$). There were no significant changes in CP estimates from either the linear models over time or between groups (Table 2 and Figure 3). The $W'$ increased significantly more in the strength training group compared with the control group for the linear (P) model (+40% vs. +4%; $p = 0.006$) and for the linear ($W'$) model (+44% vs. +5%; $p = 0.008$) and tended to increase more after strength training for the nonlinear model (+62% vs. +8%; $p = 0.065$) (Table 2 and Figure 3). For some subjects, each model produced standard errors of estimate that were greater than 5% of the CP estimate either preintervention or postintervention (Table 2). After removing these subjects from the analyses for each model (9), the time effects and group × time interactions were unchanged. In the strength training group, the change in $W'$ was inversely correlated to the change in CP using the nonlinear model ($r = −0.70, p = 0.006$) but was not significantly correlated to changes in CP for the linear (P) ($r = −0.18$) or linear ($W'$) ($r = −0.14$) models.

The correlations between the changes in TTE during each constant-power bout and changes in both CP and $W'$ for each model are shown in Table 3. Changes in $W'$ using each model were consistently positively correlated with changes in TTE, particularly for $P_1$, $P_2$, and $P_3$ (mean $r$ value = 0.79; range = 0.46–0.96). Although consistently positive, the changes in $W'$ were not significantly correlated with changes in TTE for $P_4$ (mean $r$ value = 0.38). Conversely, no consistent trends were observed for the relationships between the changes in CP and TTE. Paradoxically, for the nonlinear model, the correlations between change in TTE and change in CP were generally negative.

## DISCUSSION

Our results indicate that strength training elicited significant improvements in lower body strength and increased tolerance for exercise in the severe-intensity domain. This was illustrated by greater TTE during all 4 high-intensity constant-power exercise bouts after training and by attaining a higher PP during the postraining incremental exercise test. Therefore, our strength-training stimulus was adequate to test our hypothesis. Our findings are consistent with those of previous studies showing that traditional strength training can improve endurance performance (17,18,25,38). However, despite significant (~24–50%) improvements in TTE at each of the 4 constant-power exercise bouts used to construct the power-duration hyperbola for each subject, CP was not increased. In fact, results from the nonlinear model indicated that CP tended to decrease by an average of 5 W after training. This suggests that both linear and nonlinear formulations of the power-duration hyperbola are not satisfactory for assessing changes in CP after this type of training. Furthermore, correlations between changes in CP and TTE after strength training were generally poor and inconsistent (Table 3). Paradoxically, for

![Table 3. Correlation matrix for the change in time to exhaustion during each constant-power exercise bout, CP, and $W'$ in the strength training group, $N = 14$.](image-url)
the nonlinear model, the only statistically significant correlations were negative. This provides further evidence that improvements in endurance performance elicited by strength training are not predicted well by CP.

In contrast to the results for CP, and in support of our hypothesis, all models revealed significant increases in $W'$. The 43–53% increases in $W'$ in our subjects (Table 2) are consistent with, but somewhat higher than, the 39% increase in $W'$ reported by Bishop and Jenkins (4). The curvature constant, $W'$, is thought to represent a finite amount of work that can be performed above CP, regardless of the rate at which the work is performed. Although originally presented as parameters that represent primarily aerobic (CP) and anaerobic ($W'$) work capacities, such a dichotomous distinction is overly simplistic (21). For example, hyperoxia has been reported to increase CP but decrease $W'$(42). This observation is not consistent with the notion that $W'$ represents a finite anaerobic energy reserve (21). The precise magnitude of $W'$ may depend on a number of factors, including available anaerobic energy capacity, $V_{O_{2}}$peak, and the kinetics of $V_{O_{2}}$ in the severe-intensity domain (6). Nonetheless, $W'$ likely reflects some measure of anaerobic work capacity (16,26–28,31,40). Creatine loading increases $W'$ (26) and glycogen depletion reduces $W'$ (27). $W'$ also is correlated with tests of anaerobic work capacity (28,40) and with muscle anaerobic adenosine triphosphate production (16). Thus it could be expected that strength training would increase $W'$, as strength training has been shown to increase anaerobic work capacity as measured with 30-second all-out cycle ergometer sprint (Wingate) tests (31).

Perhaps most importantly, and in contrast to the findings for CP, the changes in $W'$ showed consistently positive correlations with the changes in TTE, especially at the 3 highest power outputs (Table 3). The 3 highest power outputs produced TTE in the range of $-1–15$ minutes. This time range encompasses race durations for a large percentage of events in endurance sports such as swimming and running events in track and field. Thus $W'$ may be useful in tracking or predicting endurance performance in these and other sports requiring all-out efforts in the range of $-1–15$ minutes. Our previously published test-retest data (15) indicated very good reliability for estimation of $W'$ (ICC = 0.879), providing additional support for the use of $W'$ as a predictor of endurance performance improvement after strength training.

It has been reported that $W'$ may decrease after endurance training that increases CP (15,20,41). In our previous work (15), we demonstrated that the increase in CP after aerobic exercise training was inversely correlated with the change in $W'$ ($r = -0.76$). In the present study, the correlation between the changes in CP and $W'$ was influenced by the model, ranging from $-0.70$ for the nonlinear model to nonsignificant $-0.18$ and $-0.14$ correlations for the linear models. Bishop and Jenkins (4) reported a strong inverse correlation ($R = -0.94$) between changes in CP and $W'$ after 6 weeks of strength training. Thus an intervention such as strength training that produces a significant increase in $W'$ may reduce the estimate of CP. A large increase in $W'$ (rightward shift of the power-duration hyperbola) that occurs with strength training may “flatten” the hyperbola (Figure 3A), with a resulting curve fit that reduces CP in proportion to the increase in $W'$. This would also have an effect on the linear formulations as well, affecting either the slope (linear [$P'$] or y intercept (linear [$P$]). It is also possible that more data points are needed to better characterize the power-duration hyperbola. For our subjects, the relative increase in TTE for the $P_3$ exercise bout (50%) was twice that of the $P_3$ exercise bout (24%). These disproportionate increases in TTE at the 2 lowest constant-power exercise bouts may have contributed to the trend for a decrease in CP obtained with the nonlinear model. However, statistical analyses conducted with all 3 models on only those subjects with SEE values less than 5% of the CP estimates both before and after strength training showed trends for a decrease in CP. Therefore, it is not likely that the observed decrease, or no change, in CP was due to poor model fit.

In conclusion, we have demonstrated that currently used linear and nonlinear formulations of the power-duration hyperbola do not produce estimates of CP that reflect the obvious improvements in tolerance to exercise in the severe-intensity domain. The $W'$, on the other hand, was significantly improved after strength training, and the improvements in $W'$ were strongly correlated with improvements in TTE.

**Practical Applications**

Critical power modeling produces parameter estimates, CP and $W'$, that reflect the capacity for high-intensity exercise tolerance and has been shown to be useful in monitoring endurance sports performance and assessing effects of various training programs. The results of this study suggest that CP testing be used with caution when evaluating the effects of strength training on endurance capacity. It is likely that the significant increases in time to exhaustion we observed for a large range of exercise intensities in the severe domain would correspond to improvements in race times of similar durations (i.e., $\sim1–15$ minutes). The increase in TTE were not reflected by changes in CP, suggesting that CP by itself may not provide useful information regarding endurance performance improvements accompanying strength training. Conversely, estimates of $W'$ were significantly increased in response to strength training, and these changes were highly correlated to the changes in TTE during severe-intensity exercise. The fact that all 3 models produced similar positive correlations between increases in $W'$ and improvements in TTE suggest that both linear and nonlinear models can be used to monitor changes in this parameter during a strength training program.

**References**

Strength Training and Critical Power


