

The Effect of Oral Creatine Supplementation on the Curvature Constant Parameter of the Power-Duration Curve for Cycle Ergometry in Humans

Akira MIURA, Fumiko KINO, Saori KAJITANI, Hironori SATO*, Haruhiko SATO†, and Yoshiyuki FUKUBA

Department of Exercise Science and Physiology, School of Health Sciences, Hiroshima Women's University, Hiroshima, 734-8558 Japan;

*Department of Electronics, Hiroshima Institute of Technology, Hiroshima, 731-5193 Japan; and

†Department of Ergonomics, Kyushu Institute of Design, Fukuoka, 815-8540 Japan

Abstract: For high-intensity cycle ergometer exercise, the tolerable duration (t) is well characterized as a hyperbolic function of power output, $P: t = W'/(P - \theta_F)$, where θ_F may be termed the "fatigue threshold." The purpose of this study was to determine the effect of oral creatine (Cr) supplementation on the curvature constant parameter (W') of the power-duration curve. A double-blind research method and a cross-over design were employed for creatine/placebo supplementation. Eight healthy male subjects (aged 18 to 22 years) each performed four or five high-intensity square-wave exercise bouts on an electrically braked cycle ergometer after 5 d of Cr monohydrate (CR: 20 g of Cr with artificial sweetener/d) or placebo (PL: 6 g of glucose/d) supplementation. Each subject performed a single high-

intensity exercise trial per day for four or five successive days to determination the P - t hyperbolic relation. After 6 weeks (the washout time of Cr from the muscles), each subject performed the other condition (i.e., PL or CR) and repeated the same experimental procedure. There was no significant difference for θ_F between PL and CR conditions (PL: 214.4 ± 23.6 , CR: 207.0 ± 19.8 W, mean \pm SD). In contrast, W' was significantly increased by the Cr supplementation (PL: 10.9 ± 2.7 , CR: 13.7 ± 3.0 kJ; $p < 0.05$). The results indicated that Cr and/or PCr content in muscles seems to be one of the important determinants of the curvature constant parameter (W') of the power-duration hyperbolic curve for cycle ergometry. [Japanese Journal of Physiology, 49, 169–174, 1999]

Key words: high-intensity cycling, power-duration curve, creatine supplementation, anaerobic working capacity.

The tolerable duration (t (s)) of high-intensity constant load cycle ergometer exercise is well characterized as a hyperbolic function of power output (P (W)),

$$t = W'/(P - \theta_F), \quad (1)$$

where θ_F (W) is the power asymptote and termed "fatigue threshold" or "critical power (CP)," and W' (J) is the curvature constant that is considered to represent a constant amount of work which can be performed

above θ_F [1–5]. This hyperbolic relation between power and its endurance time also characterizes exhausting dynamic contractions in local muscle groups [6], treadmill running [7], and swimming [8] with velocity being used instead of P . If hyperbolic, the P - t relation may be linearized by relating the power to the inverse of time, i.e.,

$$P = W' \cdot (1/t) + \theta_F. \quad (2)$$

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Correspondence should be addressed to: Akira Miura, Department of Exercise Science and Physiology, School of Health Sciences, Hiroshima Women's University, 1-1-71, Ujina-Higashi, Minami-ku, Hiroshima, 734-8558 Japan. Tel: +81-82-251-9765, Fax: +81-82-251-9405, E-mail: miura@hirojo-u.ac.jp

The linearity confirms whether the relation between the power and its tolerable duration is, in fact, hyperbolic.

The physiological nature of θ_F has already received considerable examination [5]. The curvature constant (W'), being the product of power and time, is equivalent to a constant utilizable amount of energy above θ_F . It is postulated as a finite available energy store including the phosphagen pool, a glycogen content related to anaerobic glycolysis, and an O_2 store, which is contributory to the O_2 deficit [2, 4–6]. Recently, W' has been termed “anaerobic working capacity (AWC)” because it was associated with several previously established indicators of anaerobic capacity, namely Wingate tests [9–11] and maximal O_2 deficit [12].

To date, however, the physiological basis of W' has received little consideration compared to θ_F , and, hence, is more conjectural. Glycogen depletion diminishes W' , indicating the muscle glycogen store seems to be one of the determinants of W' [13]. It has been widely demonstrated that oral creatine monohydrate supplementation enhances muscular PCr stores [14–18]. These increased PCr stores have been associated with the improving performance induced by intermittent high-intensity exercise [14, 19–21]. These results suggest that Cr supplementation affects the onset of muscular fatigue in skeletal muscle engaged in intermittent maximal contractions. Furthermore, Jacobs *et al.* [22] reported that ingesting Cr monohydrate for 5 d increases the anaerobic exercise capacity (i.e., maximal O_2 deficit) in high-intensity cycle exercise. However, little is known about the effects of Cr supplementation on the performance of sustained, constant power high-intensity exercise. Since the curvature constant of P - t relation has been proposed to reflect an anaerobic energy “store,” examining the influence of muscle PCr store is likely to improve our understanding of the physiological determinants of this relation. It was the purpose of this study, therefore, to examine W' under conditions in which one of its postulated physiological determinants, the muscle PCr store, was experimentally increased.

METHODS

Subjects. Eight healthy male subjects volunteered to participate in this study (Table 1). Each subject was informed of the risks associated with the project and gave written consent to participate in this study.

Measurements. Each subject performed the exercise tests on an electrically braked cycle ergometer (RS 232C-XL; Combi Co., Japan) in which work rate

Table 1. Physical characteristics of subjects.

Subj.	Age (years)	Height (cm)	Weight (kg)		Body fat (%)	
			PL	CR	PL	CR
1	20	170	68.8	71.6	18.8	20.0
2	18	167	55.9	57.5	15.6	15.3
3	19	167	61.6	63.7	16.4	17.2
4	21	175	63.8	63.2	19.5	19.5
5	21	167	69.1	68.9	17.4	17.4
6	20	184	83.0	82.6	20.2	20.8
7	20	168	62.0	63.6	17.5	17.5
8	22	181	70.5	70.5	18.8	20.4
Mean	20	172.4	66.8	67.7	18.0	18.5
SD	1.2	6.8	8.1	7.6	1.6	1.9

is independent of pedaling frequency between 30 and 90 rpm. Firstly, the subjects performed an incremental exercise test to determine the $\dot{V}O_{2\max}$. After 4 min of 20 W cycling to warm up, the work rate was increased at a rate of 25 W every minute until exhaustion. Each subject subsequently undertook at least four different high-intensity square-wave exercise bouts to the limit of tolerance under both placebo (PL) and Cr supplementation (CR) conditions to estimate θ_F and W' [3, 5, 7, 12]. Each trial consisted of a 15 min quiet rest in a supine position, 4 min warm-up of 20 W cycling, single high-intensity (175 to 400 W) square-wave exercise, and 6 min of 20 W cycling for cooling down. The work rate was chosen to have the exercise time to exhaustion in the range of approximately 2 to 10 min according to the $\dot{V}O_{2\max}$ of each subject. The order of the exercise bouts was randomized. For all exercise tests, the pedaling rate was 60 rpm and exhaustion was defined when the subject could no longer maintain the pedaling rate above 50 rpm despite coercion. The subjects were not told for how long or at what power they were exercised. The P - t data, under either PL or CR conditions for each subject, were used to calculate the θ_F and W' using linear regression (Eq. 2) on the plot of power against the inverse of time (Fig. 1).

Ventilatory and gas exchange responses were measured breath-by-breath during the exercise tests using an integrated computerized system (RM-300; Minato Medical Co., Japan). Prior to each exercise test, a hot-wire flow-sensor and gas analyzers were calibrated by inputting a known volume of room air at several mean flow rates and gas mixtures of known concentration, respectively. The heart rate (HR) was monitored by a cardiograph. Room air was kept at $25 \pm 1^\circ\text{C}$ by a thermal feedback device.

Maximal voluntary isometric strength was measured by using a specially designed straining device.

namometer (TD-300A; TEAC Co., Japan) at a knee angle of 90°. Each subject performed five bouts of 30 successive maximal isometric contractions (2 s contraction and 1 s interval) interspersed with 1 min recovery periods after 5 d of supplementation for both PL and CR.

Creatine supplementation. Subjects were given a 5-d supply of creatine monohydrate (Creat; Imuno Bio Japan Co., Japan) plus artificial sweetener or a glucose placebo. A double-blind cross-over design was adopted. Each subject was randomly assigned to one of two groups, PL or CR. All subjects were asked to dissolve their supplement in warm caffeine-free coffee and ingest it after each of their 3 daily meals. For the CR condition, each subject consumed 20 g of Cr per day (three times per day, 6 or 7 g of Cr+0.5 g of artificial sweetener) for 5 successive days. This 20 g/d for 5 d oral Cr supplementation regimen (so-called "100 g dosing") is well-known to significantly increase the skeletal muscle Cr and PCr stores [16, 18, 21]. We preliminarily confirmed that the "100 g dosing" Cr supplementation increased PCr stores significantly in rectus femoris muscle by ^{31}P -MRS in our previous study [23]. The PL condition followed the same regimen except that 2 g of powdered glucose were consumed after each meal. After 5 d of supplementation of CR or PL, all subjects performed a single high-intensity exercise trial to determine the P - t hyprebotic relation each day for four or five successive days. During this time, each subject ingested 2 g of Cr and 0.5 g of artificial sweetener (CR) or 1 g of powder glucose (PL) once per day. After 6 weeks (it was determined according to the washout time course of Cr from muscle [17]), each subject repeated the same exercise conditions, but with the opposite supplementation. All subjects were asked not to undertake any exercise during the 5 d of supplementation and experimental periods. For all exercise tests, the experimenters conducting the tests and the subjects were naive to the supplement condition.

Statistical analysis. Differences in the parameters between PL and CR states were evaluated by the Wilcoxon matched-pairs signed-rank test. For the relative change of total strength, 30 successive maximal voluntary isometric contractions of knee extensor, an one-way analysis of variance (ANOVA) with a Fisher post-hoc test, were applied for each CR/PL condition to determine which bout(s) showed a significant decrease for the 1st bout. All analyses were conducted using Stat View ver. 4.5 (Abacus Concepts Inc., USA). Significance was declared when $p < 0.05$.

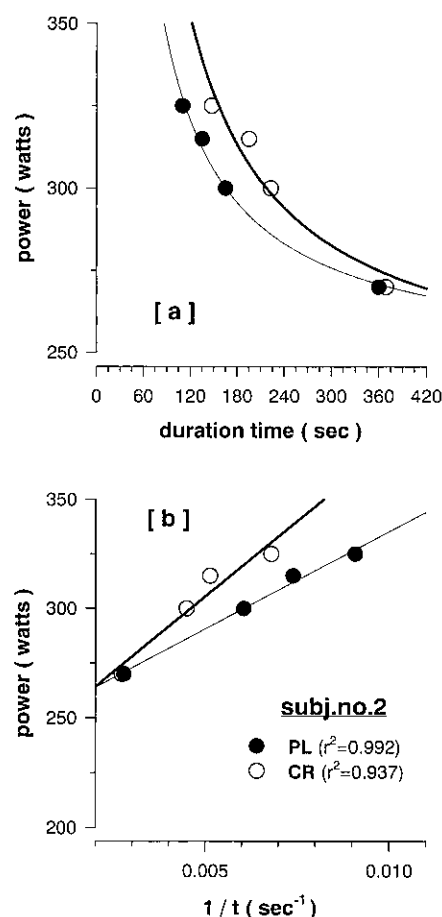


Fig. 1. Typical example of the power-duration relationships under Cr supplementation (CR: open circle) and placebo (PL: closed circle) conditions (subj. No. 2). [a] Power versus time to exhaustion at different power outputs. [b] Power versus the inverse of time for data in the top panel. Each estimated curves under CR or PL conditions are shown in bold or solid line, respectively.

RESULTS

Results from one subject for a set of P - t relationships under both PL and CR conditions are shown in Fig. 1a. As for the example shown in Fig. 1b, all subjects displayed a high degree of linearity in the relation between power and the inverse of time (Eq. 2) under either PL or CR states [correlation coefficients: r , PL=0.954–1.000, CR=0.956–0.999].

Effects of Cr supplementation on θ_F and W' are presented in Fig. 2. There was no significant difference for θ_F between PL and CR conditions [PL: 214.4 ± 23.6 , GD: 207.0 ± 19.8 W (mean \pm SD)]. In contrast, the Cr supplementation increased W' significantly compared to that with PL [PL: 10.9 ± 2.7 , CR: 13.7 ± 3.0 kJ; $p < 0.05$]. The rate of increase of W' after Cr supplementation (i.e., $(\text{CR} - \text{PL})/\text{PL}$) for all our subjects demonstrated a wide range of values from 0.05 to 0.78.

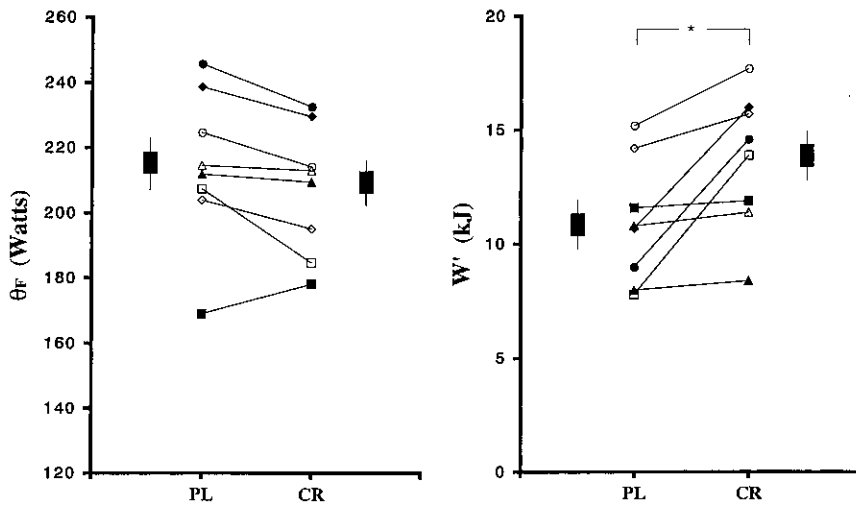


Fig. 2. Effects of Cr supplementation on P_F and W' of the P - t hyperbolic curve. * shows the significant difference between PL and CR conditions ($p < 0.05$). Large closed square with vertical bar indicates mean \pm SEM.

Table 2. The mean and individual peak values of cardio respiratory variables attained during four or five high-intensity exercise bouts under PL and CR conditions.

Subj.	$\dot{V}E$ ($l \cdot \min^{-1}$)		$\dot{V}CO_2$ ($ml \cdot \min^{-1}$)		$\dot{V}O_2$ ($ml \cdot \min^{-1}$)		HR (bpm)	
	PL	CR	PL	CR	PL	CR	PL	CR
1	113.3	144.7	4,167	4,337	3,513	3,743	167.3	165.3
2	107.5	141.3	3,515	3,243	2,658	2,947	183.5	174.0
3	109.5	129.7	3,675	3,598	3,058	2,975	175.0	178.0
4	128.5	121.0	3,923	4,380	3,453	3,783	161.0	183.7
5	110.5	122.3	3,783	3,685	2,873	2,830	176.5	177.3
6	121.0	125.0	3,217	3,337	2,740	2,620	174.0	177.0
7	133.0	121.0	4,045	4,030	3,393	3,245	180.8	168.0
8	123.3	115.0	3,597	3,520	3,033	2,933	170.0	162.3
Mean	118.3	127.5	3,740	3,766	3,090	3,135	173.5	173.2
SD	9.5	10.5	307	435	330	425	7.3	7.3

PL, placebo supplementation; CR, creatine supplementation.

The mean and individual peak values of cardiorespiratory variables attained during the high-intensity exercise bouts of each subject are shown in Table 2. The peak $\dot{V}O_2$, the peak HR, the peak $\dot{V}E$, and the peak $\dot{V}CO_2$ for the subjects in the CR group was not significantly different from that in the PL group.

All subjects performed five bouts interspersed with 1 min recovery periods of 30 maximal isometric contractions (2 s contraction and 1 s interval) after 5 d of supplementation of PL or CR. Relative change of total muscle strength of 30 repeated maximal isometric contractions for each bout was expressed as a percentage of the 1st bout for PL and CR conditions. In the PL condition, there was a significant decrease for relative change of total muscle strength between the 1st and 5th bouts ($p < 0.05$). There was no significant difference between the 1st to 5th bouts under the CR condition (Fig. 3).

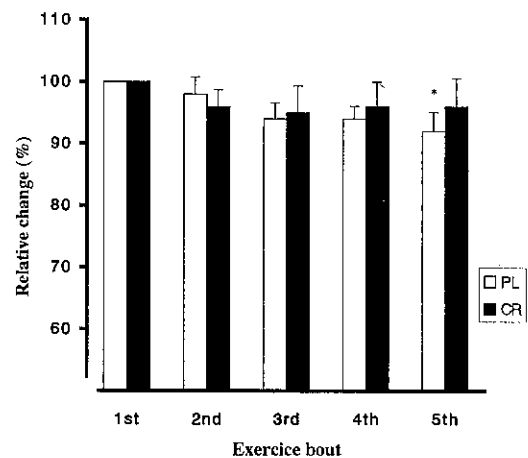


Fig. 3. Relative change of total muscle strength of 30 repeated maximal isometric contractions for each bout expressed as a percent of the 1st bout for PL and CR. Values are mean \pm SEM. * shows the significant difference between the 1st and 5th bouts under the PL condition ($p < 0.05$).

DISCUSSION

For both CR and PL conditions, the power-duration relation remained hyperbolic, but the parameters describing the relation were different. Whereas θ_F was not significantly affected, W' was improved significantly by the CR supplementation in all subjects. These characterizations, along with the experimental results of a positive association between W' and the results of the Wingate test [9–11] or maximal O_2 deficit [12] suggest that W' may be an index of “anaerobic work capacity” [5, 6, 9]. It was reported that low-intensity continuous exercise training (i.e., training intensity below θ_F) increased θ_F without altering W' for higher intensity endurance training [4, 24]. Interestingly, W' was reported to be increased by high-intensity interval training without altering θ_F [25]. While it would be premature to draw conclusions concerning the validity of W' as an anaerobic working capacity because of the questions whether such indirect indicators (i.e., Wingate test and maximal O_2 deficit) are a valid criterion of anaerobic capacity, our results suggest that the muscular Cr/PCr store, a major anaerobic energy resource for such high-intensity exercise, is a significant determinant of the curvature constant parameter W' of the P - t hyperbolic curve. That is, the degree to which the exercise tolerance was enhanced by Cr supplementation was proportionally greater at work rates requiring greater rates of anaerobic energy transduction.

Peak $\dot{V}O_2$ and HR attained in the high-intensity square-wave exercise of each subject in the CR group did not significantly differ from those in the PL group (Table 2). Also, the peak $\dot{V}E$ and $\dot{V}CO_2$ attained the same level at exhaustion during each exercise (Table 2). This confirms that the physiological stress of the subjects in the CR and PL groups was similar during high-intensity square-wave exercise.

Five days of repeated daily ingestion of Cr has been shown to elevate resting levels of muscle-free Cr and PCr, resulting in an increase in the total Cr/ATP ratio [16, 26]. While we did not directly measure the Cr and PCr of the working muscles in this study, many previous studies have demonstrated increased Cr and PCr stores using a similar dosing [16, 18, 21]. We non-invasively tried to confirm the effect of Cr supplementation on the muscular PCr stores by ^{31}P -MRS in the preliminary study. The Cr supplementation (same manner of this experiment) increased rectus femoris muscle PCr stores significantly, whereas no detectable change was recognized for the placebo condition [23]. Furthermore, Greenhaff *et al.* [21] used muscle biopsies to confirm that oral Cr monohydrate supplementa-

tion enhances muscular Cr and PCr stores. In addition, they had the subjects perform 30 successive maximal voluntary isokinetic contractions of knee extensor before and after 5 d of Cr or placebo ingestion. The rate of torque decline during the consecutive 30 isokinetic contractions was found to be significantly less after Cr ingestion as compared with contractions performed by the same subjects without supplementation. In the present study, a similar design was used for comparison. Each subject performed five bouts of 30 voluntary maximal isometric contractions (2 s contraction and 1 s interval) interspersed with 1 min recovery periods after 5 d of supplementation of PL or CR. In the PL condition, a significant decrease in relative change of total strength was observed between the 1st and 5th bouts of 30 maximal isometric contractions ($p < 0.05$). However, there was no significant difference observed from the 1st to any subsequent bout under the CR condition (Fig. 3). It seems that the CR condition improves energy substrate availability by increasing the Cr and PCr stores of working muscle during maximal isometric contractions.

Many studies have demonstrated that “Cr loading” is achievable in normal healthy individuals [14–16, 18–21, 26]. However, William *et al.* [27] reported that oral creatine supplementation does not positively affect power output or fatigue resistance during continuous high-intensity bicycle exercise in untrained men. The effect of Cr supplementation on the muscle total Cr concentration for each subject depends on their initial muscle total Cr concentration [15]. Furthermore, the increase of Cr concentration with Cr supplementation may be most dramatic in vegetarians, who will obviously have a low dietary Cr intake and have been shown to have a reduced total body Cr pool [28]. The subjects in this study were healthy untrained Japanese men. It is well-known that Japanese also have a lower dietary Cr intake similar to vegetarians. The different magnitude of the muscle Cr increase depending on the initial concentration may be one of the reasons for the inter-subject variability to improve W' by Cr supplementation.

In conclusion, this study demonstrated that the curvature constant parameter (W') was significantly increased by Cr supplementation without altering θ_F . The results indicate that the Cr and/or PCr content in muscles seems to be one of the important determinants of the W' of the power-duration hyperbolic curve for cycle ergometry.

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