



# Journal of Exercise Physiology **online** (JEP **online**)

Volume 8 Number 1 February 2005

## Managing Editor

Tommy Boone, Ph.D.

## Editor-in-Chief

Robert Robergs, Ph.D.

## Review Board

Todd Astorino, Ph.D.

Julien Baker, Ph.D.

Tommy Boone, Ph.D.

Lance Dalleck, Ph.D.

Dan Drury, DPE.

Hermann Engels, Ph.D.

Eric Goulet, M.Sc.

Robert Gotshall, Ph.D.

Len Kravitz, Ph.D.

James Laskin, Ph.D.

Jon Linderman, Ph.D.

Derek Marks, Ph.D.

Cristine Mermier, Ph.D.

Daryl Parker, Ph.D.

Robert Robergs, Ph.D.

Brent Ruby, Ph.D.

Jason Siegler, Ph.D.

Greg Tardie, Ph.D.

Ben Zhou, Ph.D.

Official Research Journal  
of The American Society of  
Exercise Physiologists  
(ASEP)

ISSN 1097-9751

## Metabolic Responses to Exercise

### ASSESSMENT OF THE ERGOGENIC PROPERTIES OF CREATINE USING AN INTERMITTENT EXERCISE PROTOCOL

HAVENETIDIS K.<sup>1,2</sup>

<sup>1</sup>Hellenic Army Academy, Division of Physical and Cultural Education, Athens, GREECE

<sup>2</sup>Leeds Metropolitan University, Carnegie Physical Education and Sports Studies, Leeds, U.K.

## ABSTRACT

**Havenetidis K.** Assessment Of The Ergogenic Properties Of Creatine Using An Intermittent Exercise Protocol. *JEPonline*. 2005;8(1):26-33. This study assessed the effect of acute creatine monohydrate (CR) loading on creatine phosphate (CrP), adenosine triphosphate (ATP), lactate (La), mean power (MP), minimum power (MIP) and mean pedal rate (MPR) during three 30 s Wingate tests (WinT). Seven male active subjects had a muscle biopsy at rest and after the 3<sup>rd</sup> WinT pre and post 25g of Cr for 4 days. ATP and CrP concentrations after the 3<sup>rd</sup> WinT were significantly ( $p < 0.05$ ) higher pre vs. post Cr ( $12.0 \pm 1.1$  vs  $16.0 \pm 3.2$  and  $10.3 \pm 1.4$  vs  $13.2 \pm 5.1$  mmol/kg of dry muscle respectively). Performance was also improved significantly ( $p < 0.05$ ) following Cr supplementation, where MP, MIP and MPR were  $598 \pm 65$  vs  $649 \pm 62$  Watts,  $382 \pm 51$  vs  $424 \pm 46$  Watts and  $108 \pm 10$  vs  $115 \pm 9$  rev/m, respectively. Performance improvement became greater at the 3<sup>rd</sup> WinT with mean percentage improvement being 6.3%, 6.7% and 10.0% for the 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> WinT respectively. In conclusion, the present CR regimen significantly increased muscle ATP and CrP, did not alter blood lactate, and led to significantly improved performance especially towards the end of the exercise protocol, possibly via an accelerated ATP and CrP re-synthesis during the recovery period between bouts.

**Key Words:** ATP, Creatine Phosphate, Phosphagen system, Sprints, Performance, Recovery, Rephosphorylation

## INTRODUCTION

Creatine (CR) ingestion has been widely used as a nutritional ergogenic aid. However, the magnitude of performance improvement reported in the literature varies considerably (4 to 100% improvement) (1,2), and such variability is probably explained by study differences for dietary, exercise and recovery conditions, training differences in the protocols, and subjects.

It has been proposed that the main benefit of Cr loading is that it increases free muscle CR, thus allowing for a greater rate of creatine phosphate (CrP) re-synthesis in the recovery from intense exercise (3). As such, research protocols need to have multiple bouts of intense exercise, separated by sufficient recovery to allow partial but incomplete CrP re-synthesis (~4 min) in order to test the complete ergogenic potential of CR loading. For example, a greater rate of CrP re-synthesis in the recovery bout would increase muscle CrP and ATP, lower muscle ADP, and as such, improve the muscle phosphorylation potential. It has been suggested (9) that in a 3 x 30s sprint separated by 4 min rest periods, the fraction of ATP supplied by CrP could be increased from 25% to 50%. This translates into a 5-10% increase in energy supply, which would dramatically improve intense exercise performance. Our prior research (10,11) also supports these hypotheses.

The purpose of this study was to investigate whether acute creatine loading could delay the onset of fatigue during repeated bouts of maximal cycling and to study any associated changes in muscle metabolism.

## METHODS

### Subjects

Seven active subjects with mean age, height and mass of  $24.4 \pm 2.4$  yrs,  $179 \pm 16$  cm and  $77.3 \pm 9$  kg, volunteered to participate after signing an informed consent approved by the Ethics Committee of the Local General Infirmary.

### Experimental protocol

The research design involved a single group experimental design, where subjects completed both control and experimental conditions. The experimental protocol involved two weeks of testing. In the first week no supplements were given (Control condition, CON) while in the second week CR was ingested (Experimental Condition, CR). Regarding the order of the treatment, as the kinetics of creatine washout has not been firmly established, creatine supplements were provided in the 2<sup>nd</sup> week in order to avoid a possible carry-over effect. Placebo supplementation was not used in this study since no significant placebo or/and learning effects were shown in previous studies where the same subjects were recruited, following the same exercise protocol (10,11).

### Creatine supplementation

During creatine supplementation subjects ingested 25 g of creatine monohydrate/day in 5g doses every two hours, for a period of four days. All beverages were prepared at University Campus, by mixing creatine, in powder form (CHEMIE-LINZ), with 300 mL of hot-warm water. Subjects ingested the CR supplementation with morning, mid-day and evening meals. Each beverage was prepared by the supplement administrator immediately prior to the ingestion, and in the absence of the subjects. Following beverage consumption all empty packets were returned and 100% compliance for supplementing was reported by all subjects. The author has chosen not to use carbohydrates mixed with creatine, in order to investigate firstly the muscle metabolism response to pure creatine ingestion and then to proceed to the addition of carbohydrates on future studies. Subjects' normal patterns of eating or training were not altered during the supplementation period.

### Exercise

All subjects, prior to the commencement of the exercise protocol and within a three-day period, performed a series (4-8) of 6 s cycle sprints to familiarize subjects to research methodologies. On the day of testing subjects were asked to attend the laboratory after a predetermined breakfast

(toast with margarine and orange juice) and not to participate in any kind of intense exercise for the prior 48 hours.

The exercise protocol involved three 30 s WinT with 6 min unloaded active recovery (60 rev/min) between each. This protocol was completed twice; under CON and CR conditions (the day following the last creatine dose) during the first and second week respectively. Before starting the test a belt, which was attached to the wall at one end, was passed around subject's waist in order to prevent the subject rising out of the saddle. The saddle height was adjusted so that when the foot was resting and the pedal was at its lowest point, there was a flexion of 15° at the knee. A standardised warm-up was performed which involved 5 min cycling at 60 Watts immediately followed by one 2 s sprint. The warm up was followed by a 5 min rest period where the subjects remained seated. The subjects were then asked to reach a rolling start (80 rev/min), and following a countdown, to cycle maximally for the specified time period and avoid pacing. All subjects received strong verbal encouragement throughout the testing protocol.

The ergometer used was a MONARK 814e, which was calibrated before and after each series of tests and bolted to the floor in order to provide greater stability during maximal cycling. The resistance used in the WinT was 0.075 kg/kg body mass and all WinT indices were measured using a computer package (15). The indices measured during the Anaerobic Wingate Test were: Mean power, Minimum Power (MIP) and Mean pedal rate (MPR). Mean power was calculated as the average mechanical power output during the whole 30 s (MP 30 s) and each 10 s interval (MP 10 s). MIP was the lowest power output during any 1 s period, and MPR was the average rate of flywheel revolutions (expressed as rev/min) during the whole 30 s WinT.

## **Measurements**

### ***Muscle Sample Collection and Preparation***

Firstly, local anaesthesia (2 mL, 1% lidocaine) was given and a preliminary incision of the skin at 2 biopsy sites (2 inches apart) was made. When repeated muscle biopsies are taken with a minimum distance 3-5 cm apart, no significant differences were shown for various metabolites (16). During both CON and CR conditions the first and second muscle sample was taken at rest and at the end of the exercise protocol (3<sup>rd</sup> WinT).

All muscle biopsy samples were obtained by a percutaneous needle biopsy technique with suction. Muscle samples were obtained from the lateral portion of the quadriceps femoris muscle (vastus lateralis). The muscle samples were immediately frozen in liquid nitrogen (3-5 s from the insertion of the needle) removed from the needle (Bergstrom and Allendale Types), weighed, freeze dried over a period of 24 hr (RGR Scientific Equipment Limited) frozen at -30° and the stored in a freezer (Cliffco 857) and subsequently analysed. The muscle samples were freeze dried again twice (1hr) and weighed twice to obtain stability by completely drying the samples. Fat was removed with petroleum ether. Samples were placed twice in glass tubes containing 5 mL petroleum ether for two consecutive periods of 15 minutes. The tubes were stirred every 3 min. The muscle samples were then freeze dried twice (30 min) and weighed twice. ATP, CrP, CR, Lactate (La) were analysed in perchloric acid extracts of freeze dried muscle with the enzymatic methods described by Harris et al. (16).

The spectrophotometer used was a Beckman (DU650). All metabolite concentrations are expressed as mmol/kg dry wt. All ATP, CP and CrP values were corrected for total creatine (TCR) both during the CON and CR condition according to the method of Harris et al. (16).

### **Statistical Analyses**

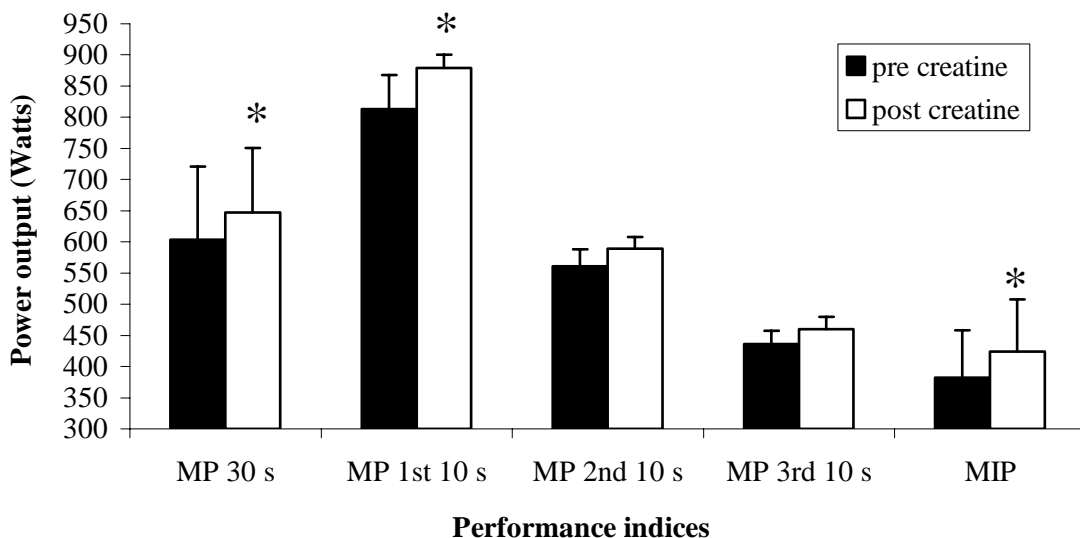
A two-way ANOVA with repeated measures on test (1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> WinT) and condition (CON, CR) was used to evaluate significance levels for all performance indices (across all WinT and for each exercise bout separately). A paired t-test was used to detect differences in body mass and muscle metabolites pre- and post-creatine supplementation. Data are presented as mean ± SD.

## RESULTS

The statistical analysis showed that CR supplementation produced a significant increase ( $p < 0.05$ ) in TCR concentration at rest ( $133.9 \pm 14.3$  mmol/kg dry muscle) compared to the values pre CR supplementation ( $115.9 \pm 15.7$  mmol/kg dry muscle).

As a consequence of CR supplementation, all subjects also showed a small but significant gain in body mass with mean values rising from  $77.3 \pm 9$  to  $78.1 \pm 9$  kg,  $p < 0.01$ ). In terms of performance during both the BAS and CR condition, highest values were achieved for MP, MIP and MPR in the 1<sup>st</sup> WinT, followed by a progressive decline for each until the end of the exercise protocol (Table 1). However, for the CR trial, these variables were significantly higher (Table 2).

Over all three WinTs, average MIP, MPR, MP 30 s and MP for the 1<sup>st</sup> 10 s improved significantly on CR by 11.5%, 7%, 7.5% and 8.5% respectively, compared to the respective values on BAS condition. MPR values pre- and post-creatine supplementation were  $108 \pm 12$  and  $115.2 \pm 9$  respectively. Power output data for all WinT indices (except MPR) pre and post CR are shown in Figure 1.



**Figure 1. Power output for various performance indices pre and post CR supplementation. \*Significantly different from baseline value ( $p < 0.05$ ).**

Across all performance indices a more pronounced performance enhancement was observed as the exercise protocol progressed (from the 1<sup>st</sup> WinT to the 3<sup>rd</sup> WinT) and differences for most of the WinT indices became significant at the 3<sup>rd</sup> WinT.

### Muscle metabolites

Data for all muscle metabolites are presented in Table 2. As expected repeated WinT produced a marked decrease ( $p < 0.01$ ) in both ATP and CrP concentrations during both the CON and CR conditions, while CR increased significantly ( $p < 0.01$ ). Furthermore, CR supplementation produced significantly ( $p < 0.05$ ) higher ATP, CrP and CR concentrations compared to the respective CON values at the 3<sup>rd</sup> WinT (33 %, 29 % and 14 % respectively;  $p < 0.05$ ). By comparing the values at rest and following the 3<sup>rd</sup> WinT, ATP and CrP concentrations decreased by 50 % ( $p < 0.01$ ) and 85 % respectively in the CON condition ( $p < 0.01$ ), while the respective values following CR were 24% and 85%, respectively. Muscle CR concentration showed a significant ( $p < 0.01$ ) but similar (between the CON and CR condition) increase from rest to the 3<sup>rd</sup> WinT (158 % and 148 %, respectively).

**Table 1. Mean  $\pm$  SD values for various performance indices during repeated WinT pre and post CR supplementation**

INDICES	BAS CONDITION			CR CONDITION		
	1 <sup>st</sup> WinT	2 <sup>nd</sup> WinT	3 <sup>rd</sup> WinT	1 <sup>st</sup> WinT	2 <sup>nd</sup> WinT	3 <sup>rd</sup> WinT
<b>MP (Watts)</b>	651 $\pm$ 112	624 $\pm$ 140	536 $\pm$ 114	701 $\pm$ 114	654 $\pm$ 104	586 $\pm$ 103*
<b>-1st 10 s</b>	868 $\pm$ 170	814 $\pm$ 161	758 $\pm$ 149	900 $\pm$ 123	879 $\pm$ 121	858 $\pm$ 119*
<b>-2nd 10 s</b>	588 $\pm$ 111	560 $\pm$ 110	534 $\pm$ 104	610 $\pm$ 108	588 $\pm$ 104	570 $\pm$ 99*
<b>-3rd 10 s</b>	457 $\pm$ 85	436 $\pm$ 84	415 $\pm$ 84	485 $\pm$ 83	466 $\pm$ 86	445 $\pm$ 84*
<b>MIP (Watts)</b>	423 $\pm$ 86	398 $\pm$ 81	325 $\pm$ 73	464 $\pm$ 102*	433 $\pm$ 96*	374 $\pm$ 62*
<b>MPR (rev/min)</b>	116 $\pm$ 9	111 $\pm$ 16	97 $\pm$ 15	124 $\pm$ 6	117 $\pm$ 11	105 $\pm$ 12*

\*Significantly different ( $p < 0.05$ ) from the values at baseline condition.

**Table 2. Mean  $\pm$  SD values for various metabolites at rest and following the 3<sup>rd</sup> WinT pre- and post-CR supplementation.**

	BAS		CR	
	Rest	3 <sup>rd</sup> WinT	Rest	3 <sup>rd</sup> WinT
<b>ATP</b>	24.3 $\pm$ 3.0	12.0 $\pm$ 1.1 <sup>†</sup>	21.1 $\pm$ 1.1	16.0 $\pm$ 3.2 <sup>†,*</sup>
<b>CrP</b>	75.2 $\pm$ 10.1	10.3 $\pm$ 1.4 <sup>†</sup>	85.3 $\pm$ 6.2	13.2 $\pm$ 5.1 <sup>†,*</sup>
<b>CR</b>	41.2 $\pm$ 8.2	106.3 $\pm$ 16.2 <sup>†</sup>	49.0 $\pm$ 8.2	121.3 $\pm$ 17.1 <sup>†,*</sup>
<b>La</b>	4.1 $\pm$ 1.2	128.1 $\pm$ 19.5 <sup>†</sup>	5.8 $\pm$ 2.1	122.7 $\pm$ 25.5 <sup>†</sup>

<sup>†</sup>Significantly different ( $p < 0.01$ ) from the values at rest. \*Significantly different ( $p < 0.05$ ) from the values at baseline condition.

## DISCUSSION

The present study examined the effects of 25 g of CR/day for four days on WinT performance indices and various muscle metabolites during an exercise protocol designed to maximally stress the CrP pathway. Evidently, CrP concentration at the end of the 3<sup>rd</sup> WinT represented only 14% of the values measured at rest. This value coincided with the results of another study (8) where CrP values represented 12% and 4% of the 3<sup>rd</sup> and the 4<sup>th</sup> bout of maximal 30 s cycling. Power output from the present study showed that the MP and MIP values at the 2<sup>nd</sup> WinT represented 94% of the value produced at the 1<sup>st</sup> WinT, whilst at the 3<sup>rd</sup> WinT, MP and MIP were equivalent to the 81% and 77% of the output measured at the 1<sup>st</sup> WinT. These data suggest that subjects were unable to reproduce their previous maximal effort throughout the present exercise protocol.

Following CR supplementation subjects were able to reduce the power decline, by presenting an average 7% increase in performance. These data agree with two studies (1,17) where a similar exercise protocol was used (3 x 30 s WinT) and performance increased by 4% and 19% respectively. The use of active subjects in this study extends our previous work (11) with recreational athletes and with multiple-sprint trained athletes (18), providing ample evidence that the present CR regime can be beneficial in intermittent sprint cycling.

It is noteworthy that performance improvement pre and post CR became greater at the end the exercise protocol. Differences pre and post CR for each WinT separately reached significance only in the 3<sup>rd</sup> WinT (except MIP where significant differences existed in each WinT); a finding which indicates that CR supplementation was more beneficial towards the end of the exercise protocol. This is supported by the significant ( $p < 0.05$ ) condition (CON and CR) by test (1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> WinT) interaction. Percentage improvement across all performance indices was 6.3%, 6.7% and 10% for the 1<sup>st</sup>, 2<sup>nd</sup> and 3<sup>rd</sup> WinT respectively. This improvement was especially noticeable for MIP, where the percentage improvement was 15% for the 3<sup>rd</sup> WinT. This finding, during conditions where the

aerobic contribution to total energy production is expected to be 35-42% (19) is in conflict with the suggestion that CR supplementation does not augment performance under aerobic conditions.

Regarding the mechanisms related to performance enhancement, an elevated pre-exercise CrP concentration was an initial “boost” to performance enhancement, followed by a more efficient replenishment of CrP stores during the 6 min intervals. Evidently, if CR supplementation had facilitated exercise performance only via elevating CP levels prior to exercise, then no further improvement would be expected beyond the 1<sup>st</sup> WinT or the greatest improvement would have occurred in the beginning of exercise. The selection of an active recovery mode in this study possibly facilitated the above mechanism since blood stagnation, as can occur with passive recovery, prevents CrP replenishment during repeated cycle sprints (20). Previous studies (8,24) on intermittent exercise have demonstrated that intramuscular triacylglycerol stores may be a potential fuel source for CrP regeneration for this type of exercise. Considering also that repeated cycle sprints with incomplete recovery also coincides with appreciable metabolic acidosis (4), a condition which favours the activity of pyruvate dehydrogenase (21), there is a possibility that aerobic metabolism (at recovery) was enhanced with the use of the present exercise protocol. Furthermore, biochemical data suggests that via metabolic compartmentalization of creatine kinase the CrP-CR pathway has “access” to both aerobic and anaerobic metabolism (22). Therefore, CR supplementation would be expected to affect both anaerobic and aerobic energy production resulting a more efficient phosphate transfer potential (6).

The fact that more work was performed following CR supplementation does not necessarily mean that the glycolytic pathway provided the “extra” ATP required to fuel muscle contraction. Firstly, higher concentrations of CrP (following CR supplementation) may inhibit phosphofructokinase activity, thereby reducing the rate of glycolysis (23). Secondly, during repeated 30 s cycle sprints it becomes increasingly difficult to re-stimulate the glycogenolytic/glycolytic pathway for ATP provision (24). Finally, following CR ingestion an increased CrP re-synthesis occurs which possibly delays the activity of glycolytic metabolism, thereby sparing muscle glycogen stores and the proton release from glycolysis (25).

## CONCLUSIONS

The present study showed that CR supplementation can improve exercise performance during exhaustive all-out intermittent cycling. Such improvement was accompanied by increases in muscle ATP and CrP. The present data also showed that the effect of CR supplementation on exercise performance was consistent and more pronounced towards the end of the exercise protocol where the aerobic contribution to ATP production increases significantly. The main mechanisms responsible for performance improvement have been suggested to be adaptations in muscle buffering capacity and an accelerated ATP and CrP re-synthesis during the recovery period.

---

## ACKNOWLEDGEMENTS

The author would like to thank Surgeon L. Boobis at Sunderland District General Hospital, U.K. for his generous volunteering to take the muscle biopsy samples. Many thanks also to Professor C.B. Cooke, Research Fellow R.F.G.J. King and Senior Lecturer R. Butterly at Leeds Metropolitan University, U.K. for their advice and guidance throughout the period of this study.

---

**Address for correspondence:** Dr Konstantinos Havenetidis, Hellenic Army Academy, Division of Physical and Cultural Education, Vari, 902 BΣT, Athens, GREECE

---

## REFERENCES

1. Tarnopolsky MA. Creatine monohydrate supplementation enhances high-intensity exercise performance in males and females. *Int J Sport Nutr Exerc Metab* 2000; 10(4): 452-463.
2. Prevost MC, Nelson AG, Morris GS. Creatine supplementation enhances intermittent work performance. *Res Quart Exerc Sport* 1997;68(3): 61-68.
3. Soderlund K, Balsom PD, Ekblom B. Creatine Supplementation and high intensity exercise: influence on performance and muscle metabolism. *Clin Sci* 1994; 87: 120-121.
4. Boobis LH. Metabolic aspects of fatigue during sprinting. In: Maughn RJ, Macleod D, Nimmo M, Reilly T, Williams C. (eds). *Exercise: Benefits, Limitations & Adaptations*, F.N.Spon: 1987:116-40.
5. Skinner JS, Mclellan TH. The transition from aerobic to anaerobic metabolism. *Res Quart Exerc Sport* 1980;51(1): 234-48.
6. Bessman SP, Savabi F. The role of phosphocreatine shuttle in exercise and muscle hypertrophy. In: Taylor WA, Gollnick D, Green HJ, Iannuzzo CD, Noble EG, et al. (eds). *International Series of Sports Sciences, Biochemistry of Exercise VII*. Champaign, IL: Human Kinetics, 1990:21:109-20.
7. Orland LL, Macdougall JD, Tarnopolsky M, Elorriaga A, Borgmann A, Atkinson S. The effect of oral creatine Supplementation on muscle (Pcr) and power output during a short-term maximal cycling task. *Med Sci Sports Exerc* (Suppl), 1994;26(5): 523.
8. McCartney N, Spriet LL, Heighenhauser GLF, Kowalchuk JM, Sutton JR, Jones NL. Muscle power and metabolism in maximal intermittent exercise. *J Appl Physiol* 1986;60: 1164-69.
9. American College of Sports Medicine Roundtable. The physiological and health effects of oral creatine supplementation. *Med Sci Sports Exerc* 2000;32: 706-717.
10. Havenetidis K, Matsouka R, Cooke CB, Theodorou A. The Use of Varying Creatine Regimes On Sprint Cycling. *J Sports Sci Med (online)* [http:// www.jssm.org](http://www.jssm.org) 2003; 2: 88-97.
11. Havenetidis K, Cooke CB, King RFGJ, Butterly R. The effect of creatine supplements on repeated 30 s cycle sprints in man. *J Physiol* 1994;483P:122P.
12. Havenetidis K, Matsouka R, Konstadinou V. Establishment of the highest peak anaerobic power prior to the commencement of the Anaerobic Wingate Test. *J Hum Mov Studies* 2003;44(6): 479-487.
13. Havenetidis K, Cooke CB, Butterly R. Repeated cycle sprints for the establishment of the highest peak anaerobic power in a sedentary and an athletic group. *J Sport Sci* 1995;14(1): 86.
14. Capriotti PV, Sherman, WM Lamb, DR. Reliability of power output during intermittent high-intensity cycling. *Med Sci Sports Exerc* (Suppl), 1999;31(6): 913-915
15. LaKomy HKA. Measurement of work and power output using friction-loaded cycle ergometers. *Ergonom* 1986;29(4): 509-17.
16. Harris RC, Hultman E, Nordesjo LO. Glycogen, glycolytic intermediates and high energy phosphates determined in biopsy samples of musculus quadriceps femoris of man at rest. Methods and variance of values. *Scand J Clin Lab Invest* 1974;33:109-120.
17. Earnest CP, Snell PG, Rodriguez R, Almada AL, Mitchell TL. The effect of creatine monohydrate ingestion on anaerobic power indices, muscular strength and body composition. *Acta Physiol Scand* 1995;153: 207-209.
18. Havenetidis K, Haralambidou E. Creatine ingestion and excretion in relation to exercise performance. *Proceedings of the 7<sup>th</sup> International Olympic Committee Congress*. October 8-11, 2003, Athens, GREECE.
19. Hill DW, Smith JC. Calculation of aerobic contribution during high intensity exercise. *Res Quart Exerci Sport* 1992;63(1): 85-8.
20. Spriet LL, Lindinger MI, McKelvie RS, Heigenhauser CLF, Jones NL. Muscle glycogenolysis and H<sup>+</sup> concentration during maximal intermittent cycling. *J Appl Physiol* 1989;66, 8-13.
21. Newsholme EA, Leech AR. *Biochemistry for the Medical Sciences*. New York: Wiley, 1973.

22. Walsh B, Tonkonogi M, Sodurlund K, Hultman E, Saks V, Sahlin K. The role of phosphorylcreatine and creatine in the regulation of mitochondrial respiration in human skeletal muscle. **J Physiol** 2001;15; 537(Pt 3): 971-8.
23. Storey KB, Hochachka, PW. Activation of muscle glycolysis: a role for creatine phosphate in phosphofructokinase regulation. **FEBS Lett** 1974;46:337-339.
24. Spriet LL. Anaerobic metabolism during high-intensity exercise. In: **Exercise Metabolism**, M. Hargreaves. Champaign, IL: Human Kinetics, 1995; 1-40.
25. Preen D, Dawson B, Goodman C, Lawrence S, Beilby J, Ching S. Effect of creatine loading on long-term sprint exercise performance and metabolism. **Med Sci Sports Exerc**, 2001;33(5): 814-821.
26. Birch R, Noble D, Greenhaff PL. The influence of dietary creatine Supplementation on performance during repeated bouts of maximal isokinetic cycling in man. **Eur J Appl Physiol** 1994;69:253-9.