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Review article

CREATINE SUPPLEMENTATION AND EXERCISE PERFORMANCE: A BRIEF REVIEW

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ABSTRACT

During the past decade, the nutritional supplement creatine monohydrate has been gaining popularity exponentially. Introduced to the general public in the early 1990s, shortly after the Barcelona Olympic Games, creatine (Cr) has become one of the most widely used nutritional supplements or ergogenic aids, with loading doses as high as 20-30 g· day^{-1} for 5-7 days typical among athletes. This paper reviews the available research that has examined the potential ergogenic value of creatine supplementation (CrS) on exercise performance and training adaptations. Short-term CrS has been reported to improve maximal power/strength, work performed during sets of maximal effort muscle contractions, single-effort sprint performance, and work performed during repetitive sprint performance. During training CrS has been reported to promote significantly greater gains in strength, fat free mass, and exercise performance primarily of high intensity tasks. However, not all studies demonstrate a beneficial effect on exercise performance, as CrS does not appear to be effective in improving running and swimming performance. CrS appears to pose no serious health risks when taken at doses described in the literature and may enhance exercise performance in individuals that require maximal single effort and/or repetitive sprint bouts.

KEY WORDS: Creatine supplementation, ergogenic aid, exercise performance

INTRODUCTION

During the past decade, the nutritional supplement creatine monohydrate has been gaining popularity exponentially, with reported annual sales in the U.S alone climbing from $50 million in 1996 (Bamberger, 1998) to over $400 million during 2001 (Metzl et al., 2001). Creatine supplementation (CrS) first gained popular attention in the early 1990s, after high profile Olympic athletes competing in sprint and power events at the Barcelona Olympic Games believed their performance had benefited from CrS (Anderson, 1993). Since this time creatine (Cr) has become one of the most widely used nutritional supplements with an estimated worldwide consumption of 2.7 million kilograms (Williams et al., 1999). Recently, many athletes and teams have implemented oral CrS in an effort to enhance sports performance, as CrS is not presently (October, 2003) on the banned substance list by the International Olympic Committee (2003). Thus, using this supplement would not constitute anything illegal or unethical on behalf of the athlete or coach. Consequently, Cr has risen to the top of the modern athletes shopping list.

This article does not purport to be an exhaustive review of all related published literature, however, it is the purpose of this paper to outline evidence presented and report on the usefulness of CrS as a performance-enhancing aid by identifying potential ergogenic effects related to this supplement. Readers are referred to other reviews for aspects of this topic that may not be addressed by this article (Volek and Kraemer, 1996; Mujika and Padilla, 1997; Williams and Branch, 1998; Jacobs, 1999; Wyss and Kaddurah-Daouk, 2000; Lemon, 2002).

A French scientist named Chevreul is credited

with first discovering Cr in 1832 (Williams et al., 1999), however, it was not until 1926 that scientists quantified Cr storage and retention in the body (Chanutin, 1926). Cr is a compound that is both made within the body from amino acids and obtained through diet. Most of the body's Cr is stored within skeletal muscle where it plays a role in metabolism, with the daily turnover of Cr for the average sized person of about 2 g (for review see Wyss and Kaddurah-Daouk, 2000).

Williams and Branch (1998) suggest that the adenosine triphosphate-phosphocreatine (ATP-PCr) energy system has the greatest power potential. Muscle stores of PCr may split and release energy for rapid resynthesis of ATP, although the supply of PCr is limited, with the combined total ATP and PCr capable of sustaining all out maximal effort exercise lasting up to 5 to 10 seconds (Williams and Branch, 1998). Therefore, fatigue may be attributed to the rapid decrease in PCr. Generation of peak anaerobic power and anaerobic capacity in short-term, high-intensity exercise may be dependent upon endogenous levels of ATP and PCr, particularly, PCr as a means to rapidly regenerate the limited intramuscular supply of ATP for anaerobic capacity (Williams and Branch 1998). Thus, an increase in muscle total creatine (TCr) through exogenous CrS may provide an ergogenic effect by enhancing the rate of ATP synthesis during intermittent, high-intensity, short-duration exercise and by improving the rate of PCr resynthesis during recovery (Snow et al., 1998).

This contention is supported by the findings of Kurosawa et al. (2003) who evaluated the rate of ATP synthesis through PCr hydrolysis and glycolysis and mean power output during a 10 second maximal dynamic handgrip exercise (Ex10) using 31-phosphorus magnetic resonance spectroscopy before and after CrS (30 g· day^{-1} for 14 days). ATP synthesis rate through PCr hydrolysis positively correlated with mean power output during Ex10 in all subjects after CrS ($r = 0.58$, $p < 0.05$). The authors concluded that a daily dose of 30g CrS for 14 days improved APT synthesis through PCr hydrolysis and mean power output during short-term, maximal exercise. Moreover, it is strongly indicated that an improvement in performance during Ex10 was associated with the increased PCr availability for the synthesis of ATP.

The body has several different ways in which it restores ATP. As previously stated, energy is released when one of the phosphates in ATP is cleaved off. When this happens, ATP becomes adenosine diphosphate (ADP). Returning ADP to its high-energy state of ATP by adding another phosphate group to it can then recycle ADP. One such ATP producing system is glycolysis, which is achieved anaerobically. Another system that the body extracts energy from is oxidative phosphorylation, which incorporates oxygen to yield ATP (for review see Mommaerts, 1969).

The degree to which skeletal muscle will use PCr may be intensity and duration dependant. When intensity exceeds the power of the aerobic system the muscle begins to rely on the anaerobic system, which includes the use of PCr and muscle glycogen as fuels. Consequently, during the most intense periods of exercise or sport, the muscle will tax the PCr store most highly (Wyss and Kaddurah-Daouk, 2000). Therefore, some have argued that CrS may benefit certain athletes in particular sports (Dawson et al., 1995; Meir, 1995; Schnedeider et al., 1997; Izquierdo et al., 2002).

CrS has been suggested as a means to "load" the muscle with Cr and increase storage of PCr (Dawson et al., 1995; Snow et al., 1998; Finn et al., 2001). Theoretically, this would serve to improve the ability to produce energy during explosive, high-intensity exercise bouts and/or enhance the ability to recover from intense exercise. In support of the contention research has shown that CrS increases intramuscular PCr concentrations (Harris et al., 1992; Vandenberghe et al., 1997; McKenna et al., 1999; Stout et al., 2000). Furthermore, the CrS-related increase in PCr concentration may allow a 'mopping up' the acid producing hydrogen ions produced during the breakdown of ATP and other anaerobic processes (Vandenberghe et al., 1997; Stout et al., 2000). Therefore, PCr may contribute to the maintenance of optimal pH levels within the muscle and allows continued performance with minimal fatigue (for review see Volek and Kraemer, 1996).

WHAT DOES THE RESEARCH INDICATE?

Following the first reports by Harris et al. (1992), that PCr content in human muscle can increase up to 50% following daily CrS (5 g Cr monohydrate 4-6 × day for ≥ 2 days), a number of studies have examined the effects of CrS on muscle metabolism and/or high-intensity exercise performance. Studies that have measured muscle total creatine (TCr) (phosphocreatine + creatine) have reported an elevation in TCr after CrS involving loading phases of 20-30 g· day^{-1} for 3-6 days. Some studies found that both resting TCr and PCr content increased (McKenna et al., 1999; Smith et al., 1999; Kurosawa et al., 2003), whereas others reported significant increases in only TCr (Greenhaff et al., 1994; Becque et al., 2000) or PCr (Smith et al., 1998; Stout et al., 2000).

Theoretically, an increase in TCr stores may provide an ergogenic effect during high intensity exercise by enhancing the rate of ATP synthesis during contraction and by improving the rate of PCr

resynthesis during recovery, which may be beneficial for repeated sprint activity. A recent investigation by Mujika et al. (2000) supports such a contention, concluding that acute CrS favourably affected repeated sprint performance and limited the decay in jumping ability in highly trained soccer players. However, on the whole, experimental evidence supporting an ergogenic effect for CrS is somewhat mixed. Several studies have demonstrated improved high-intensity exercise performance after CrS (Dawson et al., 1995; Meir, 1995; Jacobs et al., 1997; Vandenberghe et al., 1997; Volek et al., 1999; Mujika et al., 2000), whereas others have reported no beneficial effects (Barnett et al., 1995; Snow et al., 1998; Deutekom et al., 2000; Gilliam et al., 2000; Finn et al., 2001; Syrotuik et al., 2001; Biwer et al., 2003).

A possible explanation for the conflicting findings may relate to the experimental design used to examine the effects of CrS on exercise performance. Most studies have employed a cross-sectional experimental design or an ordered treatment allocation. However, few studies have utilised a crossover experimental design, possibly due to the time required for muscle TCr to return to basal levels after CrS was unknown. Lemon, (2002) indicates that a variety of factors including, but not limited to, sample size, exercise modality, rest and recovery intervals, residual effects of cessation of CrS, non-responders, gender and age effects and methodology used, make any interpretation of existing Cr literature extremely difficult.

STUDIES REPORTING ERGOGENIC BENEFIT

Most studies that have investigated the ergogenic value of CrS have reported significant increases in strength/power, sprint performance, and/or work performed during multiple sets of maximal effort muscle contractions (Table 1). The improvement in exercise capacity has been attributed to increased TCr and PCr content, thus resulting in greater resynthesis of PCr, improved metabolic efficiency and/or an enhanced quality of training promoting greater training adaptations. The following literature reports ergogenic benefits of CrS.

Maximum Strength/Power

For athletes such as weightlifters and bodybuilders, gains in strength/power are often accompanied by muscle hypertrophy. Consequently, ingesting a nutritional supplement that can promote strength gains during training may be particularly beneficial. Vandenburghe et al. (1997) reported that CrS 20 g· day^{-1} for 4-d followed by 5 g· day^{-1} for 66-d promoted a 20 to 25% greater gain in 1-repetition maximum (RM) strength in untrained women participating in a 70-d resistance-training program than subjects receiving a placebo. Furthermore, the gains in strength observed were maintained in subjects ingesting creatine during a 70-d detraining period. These findings indicate that CrS during resistance training promotes significantly greater gains in strength.

Data presented by Pearson et al. (1999) revealed that athletes ingesting 5 g· day^{-1}, in conjunction with a 10 wk heavy resistance training program, significantly increases strength and power indices, and body mass when compared with a placebo group. These data also indicate that lower doses (5 g· day^{-1}) may be ingested, without a short-term, large-dose loading phase (20 g· day^{-1}), for an extended period to achieve significant performance enhancement.

A well-controlled study by Francaux and Poortmans (1999) investigated the effects of 42-d strength training and followed by 21-d of detraining on muscle strength and body mass. Subjects ingested 21 g/Cr for 5-d, following which the dose was reduced to 3 g/Cr for 58-d. No change in body mass was observed for either the control or placebo groups during the entire experimental period, while the body mass of the Cr-group increased by 2 kg. This increase was attributed partially to an increase in body water content, and more specifically, to an increase in the volume of the inter-cellular compartment. However, the relative volumes of the body water compartments remained constant. The authors suggest that the gain in body mass observed after medium-term CrS is not attributed to water retention in the cell, but probably to dry matter growth accompanied with a normal water volume.

Volek et al. (1999) randomly assigned nineteen healthy resistance-trained in a double-blind fashion to either a CrS or placebo group (25 g· day^{-1}) for 1 wk followed by a maintenance dose (5 g· day^{-1}) for the remainder of the training. Heavy resistance training was performed for 12 wks. Significant increases in body mass and fat-free mass were greater in CrS (6.3% and 6.3%, respectively) than placebo (3.6% and 3.1%, respectively). Increases in bench press and squat were greater in CrS (24% and 32%, respectively) than placebo (16% and 24%, respectively) subjects. Compared with placebo subjects, CrS subjects demonstrated significantly greater increases in Type I (35% *vs*. 11%), IIa (36% *vs*. 15%), and IIab (35% *vs*. 6%) muscle fibre cross-sectional areas. The authors concluded that CrS enhanced fat-free mass, physical performance, and muscle morphology in response to heavy resistance training, presumably mediated via higher quality training sessions.

While it is understandable that if CrS allows an athlete to train harder, athletes may become stronger over time, however, studies also indicate

Table 1. Summary of the research reporting an ergogenic effect following creatine supplementation.

Study	Protocol	Subjects	Creatine Dose	Exercise Performance
Izquierdo et al. 2002	Intermittent High-Intensity Exercise 1-RM MxS; CMJT; RPRT; MDRT	19 highly trained M handball players	20 g· day^{-1} × 5-d	Significant improvements on MxS, repetitive high-power exercise bouts & total reps to fatigue. Enhanced repeated sprint performance. Significant ↑ BM 0.6 kg
Mujika et al. 2000	Intermittent High-Intensity Exercise CMJT; 6 × 15 m sprints; IET; rec CMJT	17 highly trained M soccer players	20 g· day^{-1} × 5-7d	Improved repeated sprint performance & limited decay in jump ability. Significant ↑ BM 0.6 kg
Becque et al. 2000	Resistance Exercise Progressive weight training 2 × wk; 6 wks arm-flexor strength training`	23 resistance trained M	20 g· day^{-1} × 5-d + 2 g/d × 6 wks	29.9% increase in 1-RM arm-flexor muscular strength. Significant ↑ BM 2.0 kg; FFM 1.6 kg
Kreider et al. 1998	Resistance Exercise Progressive weight training 2 × wk; 6 wks + 12 × 6 s max cycle sprints	25 NCAA division IA M collegiate American football players	20 g· day^{-1} × 5-d	Significant ↑ in bench press lifting volume & total lifting volume. Improved sprint performance in sprints 1 to 5. Significant ↑ BM 2.4 kg
Vandenberghe et al. 1997	Resistance Exercise Progressive weight training 3 × wk; 10 wks + intermittent isokinetic arm-flexion test	19 sedentary F	a) 20 g· day^{-1} × 4-d b) 20 g· day^{-1} × 4-d + 5 g· day^{-1} × 10 wks	a) No effect on arm-flexion torque or BC b) Increase in 1-RM leg press, leg extension, squat & improved arm-flexion torque. Significant ↑ FFM 2.6 kg
Volek et al. 1997a	Resistance Exercise Bench press + jump squat 5 sets × 10 repetitions	13 resistance trained M	20 g· day^{-1} × 7-d	Significant ↑ in exercise performance. No measurable alteration in circulating testosterone or cortisol. Significant ↑ BM 1.3 kg
Jacobs et al. 1997	Cycling Cycle to exhaustion at 125% VO_2max. MAOD calculated	26 M & F varied training status	20 g· day^{-1} × 5-d	Significant ↑ in oxygen uptake, MAOD and time to exhaustion. Significant ↑ BM 0.7 kg
Dawson et al. 1995	Cycling a) 1 × 10 s max sprint b) 4 × 4 min max sprint 24 s rec between sprints	a) 18 active but untrained M b) 22 active but untrained M	20 g· day^{-1} × 5-d	a) No effect on 1 × 10 s max sprint performance b) Improved repeated sprint performance. Significant ↑ in total work & peak power
Meir, 1995	Case study survey during 5 months of professional rugby league competition	17 professional rugby league players M	5 × loading cycles 20 g· day^{-1} × 4-d followed by a 3 wk 3-d abstinence period	*Reported perceived benefits* 35.3% - Fatigue less quickly 29.4% - Quicker sprint rec 23.5% - Quicker training rec

Abbreviations: M = Male; F = Female; RM = Repetition maximum; MxS = Maximal strength; RPRT = Repeated sprint running test; MDRT = Maximal multistage discontinuous incremental running test; CMJT = Counter-movement jump test; IET = Intermittent endurance test; BC = Body composition; BM = Body mass; FFM = Fat free mass; MAOD = Maximal accumulated oxygen deficit; rec = Recovery

that short-term CrS may enhance peak power. Dawson et al. (1995) reported that CrS (20 g· day^{-1} for 5-d) significantly increased peak power during the first set of 6 × 6 s sprints performed on a cycle ergometer. An investigation by Becque and coworkers (2000) involved twenty-three male volunteers with at least 1 yr of weight training experience tested arm flexor 1-RM, upper arm muscle area, and body composition. Subjects ingested 20 g· day^{-1} for 5-d, after which, CrS was reduced to 2 g· day^{-1} for the remainder of the study. Results indicate that 6 wks of CrS during arm flexor strength training lead to greater increases in arm flexor muscular strength, upper arm muscle area, and fat-free mass than strength training alone.

Multiple Sets of Maximal Effort Muscle Contractions

One of the potentially most beneficial effects of CrS for power athletes is that supplementation has been reported to increase the amount of work performed during a series of maximal effort muscle contractions. Volek et al. (1997a) reported that CrS (25 g· day^{-1} for 7-d) resulted in significant improvements in exercise performance during five sets of bench press and jump squats in comparison to a placebo group. CrS resulted in a significant increase in repetitions performed during bench press for set 2, while peak power output significantly increased in the jump squat during set 5. The authors concluded that increases in exercise performance and body mass (1.3 kg) associated with 1 wk of CrS are not due to any measurable alteration in circulating concentrations of steroid hormones, as pre- and post-exercise testosterone and cortisol values did not differ significantly between groups. Additionally, when CrS was extended for a further 11-d (Volek et al., 1997b), significant increases were recorded in all 5 sets of bench press repetitions (~26.6%) and jump squat peak power output (~4.7%). Improvements are most likely related to an increase in energy substrate availability and resynthesis.

Moreover, results from Vandenberghe et al. (1997) indicate that CrS (20 g· day^{-1} for 4-d) increased muscle PCr concentration by 6%. Thereafter, this increase was maintained during 10 wk of training associated with low-dose creatine intake (5 g· day^{-1}). Compared with placebo, maximal strength of the muscle groups trained, maximal intermittent exercise capacity of the arm flexors, and fat-free mass were increased 20-25%, 10-25%, and 60% more, respectively, during CrS.

Sprint/High-Intensity Performance

It has also been reported that CrS may improve single effort and/or repetitive sprint performance particularly in sprints lasting 6 to 30 s with 30 s to 5 min of rest recovery between sprints. Dawson et al. (1995) found that CrS (20 g· day^{-1} for 5-d) significantly increased work performed during the first of 6 × 6 s cycle ergometer sprints with 30 s recovery between sprints. These results are supported by Schneider et al. (1997), who reported that CrS (25 g· day^{-1} for 7-d) significantly improved 5 × 15 s cycle ergometer sprints with 60 s recovery between sprints.

A case study by Meir (1995) investigated the effectiveness of repeated CrS loading phases consisting of 20 g· day^{-1} for 4-d; 1 × month, followed by a 3 week 3-d abstinence period on professional rugby league players. The author indicates that the work/rest ratio for athletes participating in this sport is approximately 1:6-1:8. This would suggest that professional rugby league could be considered an interval activity. Meir (1995) employed a 12-question survey relating to player compliance, preferred time and ingestion method, perceived side effects, and perceived benefits. The survey was complete after the third loading cycle. Of the perceived benefits 35.3% reported fatiguing less quickly, 29.4% reported quicker recovery from sprint type activity, and 23.5% reported quicker recovery from training sessions. The author concluded that CrS may be useful in sports such as rugby league that require repeat sprint efforts and that CrS may be advantageous as an aid improving both training and performance.

However, it is difficult to validate such conclusions, as several limitations appear within the experimental design. First, the loading dose (20 g· day^{-1} for 4-d) may not be adequate to achieve maximal increase in TCr concentrations. Majority of research report loading phases of 20-30 g· day^{-1} for 5-7-d (Hultman et al., 1996; Volek et al., 1997a; Snow et al., 1998; Francaux and Poortmans, 1999; Finn et al., 2001; Wilder et al., 2001; Louis et al., 2003). Secondly, the subjects undertook no dietary control. Thirdly, several methods of ingestion were employed including dissolving Cr powder in tea or coffee, cold water or juice, and taken dry washed down with fluid. Hultman et al. (1996) suggests that when CrS is in powder form doses be dissolved in ~250 ml of warm water. Alternative methods may affect the rate of absorption. Finally, the author alludes to the fact that it is not unusual for a placebo effect to be experienced by subjects taking various forms of supplementation. Therefore, caution is warranted in the interpretation of the above findings.

STUDIES REPORTING NO ERGOGENIC BENEFIT

A number of studies have reported no ergogenic benefit from CrS, although the reason for the lack of

ergogenic effect observed in these studies is sometimes not clear (Table 2). However, it is possible that individual variability in response to CrS may account for the lack of ergogenic benefit reported in these studies. For example, Greenhaff (1997) estimates that as many as 30% of individuals who undergo Cr loading protocols may not respond with augmented TCr.

Using a double-blind, placebo-control design involving 32 elite male and female swimmers from the Australian National Team, Burke et al. (1996) reported that CrS (20 g· day^{-1} for 5-d) did not enhance performance in maximal single effort swim sprints of 25 m, 50 m, and 100m each interspersed with ~10 min recovery period. Given the length of the recovery period, resynthesis of ATP would be complete without CrS, therefore, an increase in performance would not be expected. In a similar study, Mujika et al. (1996) assigned 20 male and female swimmers in a randomised, double-blind manner to either CrS (20 g· day^{-1} for 5-d) or placebo groups in order to investigate the effect on 25 m, 50 m, and 100 m swim sprint performance. They reported no performance differences between the groups, however, a significant ($p < 0.05$) increase in body weight was found in the CrS group. The authors suggested that the increase in body weight experienced by subjects following CrS could result in a concomitant increase in drag force and altered stroke mechanics. Such a mechanism is a likely reason why no ergogenic effect was present.

Performing 30 s maximal cycling (Wingate) task after CrS (20 g· day^{-1} for 3-d) Odland and coworkers (1997) found that CrS did not increase resting muscle PCr, nor did it affect the single short-term maximal cycling performance. The most likely explanation for this is that the increase in muscle TCr content after CrS was insufficient to induce an enhanced sprint performance and to allow an improved rate of PCr resynthesis after exercise. Alternatively, it is also possible that CrS does not enhance sprint performance during brief maximal exercise.

Following this line of investigation Snow et al. (1998) utilised a double-blind crossover design on untrained men performing 1 × 20 s maximal sprint on an cycle ergometer after CrS (30 g· day^{-1} for 5-d). The data demonstrated that CrS increased muscle TCr content, but the increase did not induce an improved sprint exercise performance or alterations in anaerobic muscle metabolism. In conclusion the authors reported that a small, yet significant, increase in muscle TCr content occurred but this increase, however, did not result in an improved sprint-exercise performance or any alterations in markers of muscle anaerobic energy metabolism during, and in recovery from sprint exercise.

Similar results were observed by Finn et al. (2001), who investigated the effect of CrS (20 g· day^{-1} for 5-d) on 4 × 20 s maximal sprint on an air-brake cycle ergometer, with each sprint separated by 20 s of recovery. The authors reported that, while CrS elevates the intramuscular stores of FCr, this does not have an ergogenic effect during intermittent exercise. Furthermore, Finn et al. (2001) suggest that the contents of PCr at the beginning of the second and subsequent periods of exercise could be influenced by the recovery time between the periods as well as by the initial PCr content at rest, the rate of PCr utilisation in the preceding exercise(s) and the rate of PCr resynthesis between the exercise. Since neither Snow et al. (1998) nor Finn et al. (2001) achieved a significant increase in PCr the absence of an ergogenic effect is not surprising.

Gilliam et al. (2000) examined the effect of CrS (5 g/Cr + 1 g· glucose^{-1} four times per day for 5-d) on the decline in peak isokinetic torque of the quadriceps muscle group during an endurance test. Subjects performed isokinetic strength tests that consisted of five sets of 30 maximum volitional contractions with a 1 min rest period between sets. Based on within and between group comparisons they were unable to detect an ergogenic effect of CrS on the decline in peak torque during isokinetic exercise.

In a most recent study, Delecluse et al. (2003) investigated impact of short-term (7-day), high-dose (0.35 g· kg^{-1}· d^{-1}) CrS on single sprint running performance (40 m, < 6 s) and on intermittent sprint performance in highly trained sprinters. The maximal sprint performance, the relative degree of fatigue at the end of intermittent sprint exercise (6 × 40 m, 30 s rest interval), as well as the degree of recovery (120 s passive rest) remained unchanged following CrS. There were no significant changes related to CrS in absolute running velocity at any distance between start and finish (40 m). It was concluded that no ergogenic effect on single or repeated 40 m sprint times with varying rest periods was observed in highly trained athletes. The explanation for this result may be inferred from Snow et al. (1998), who outlines that the increase in muscle TCr content after CrS was insufficient to induce an enhanced sprint performance and to allow an improved rate of PCr resynthesis after exercise.

CREATINE SUPPLEMENTATION AND HEALTH-RELATED CONCERNS

There is no definitive evidence that CrS causes gastrointestinal, renal, and/or muscle-cramping complications. A most recent investigation by Kreider et al. (2003) examined the effects of long-term CrS (up to 21 months) on clinical markers of

Table 2. Summary of the research reporting no ergogenic effect following creatine supplementation.

Study	Protocol	Subjects	Creatine Dose	Exercise Performance
Delecluse et al. 2003	Running 2 × 40 m sprint runs 5 min rec 6 × 40 m sprint runs 30 s rec	12 highly trained nationally ranked 100 m & 200 m sprinters M & F	0.35 g· kg^{-1} · d^{-1} × 6-d	No effect on sprint velocity. 0.3 kg ↑ BM n.s
Biwer et al. 2001	Running Treadmill intervals 20 min Constant spd 15% grade × 2 min 0% grade × 2 min	15 collegiate soccer players M & F	0.3 g· kg^{-1} × 6-d	No effect on sub-maximal treadmill performance interspersed with high-intensity intervals. Significant ↑ BM 1.2 kg (M)
Finn et al. 2001	Cycling 4 × 20 s max sprints 20 s rec between sprints	16 regional class triathletes	20 g/d × 5-d	No effect on multiple sprint cycle performance with intervening 20 s rest periods. Significant ↑ BM 0.81 kg
Wilder et al. 2001	Resistance Exercise Progressive weight training 4 × wk; 10 wks	25 highly trained M collegiate football players	a) 3 g· d^{-1} b) 20 g/d × 3-d + 5 g/d × 10 wks	No effect on 1-RM squat strength. Significant ↑ FFM (a) 2.46 kg (b) 1.79 kg
Gilliam et al. 2000	Isokinetic Knee Extension 5 × 30 MVC 1 min rec between sets	23 active but untrained M	20 g/d × 5-d	No effect on maintaining peak isokinetic torque. Significant ↑ BM 0.86 kg
Deutekom et al. 2000	Isokinetic Knee Extension 2 × 40 MVC Cycling 2 × 30 s max sprint	23 well trained rowers M	20 g/d × 6-d	No effect on muscle performance or maximal output during sprint cycling. Significant ↑ BM 1.6 kg
Francaux & Poortmans 1999	Resistance Exercise Isokinetic squat Periodized 3 × wk; 6 wks	25 active but untrained M	21 g/d × 5-d + 3 g/d × 58-d	No effect on mean force development. Significant ↑ BM 2 kg
Snow et al. 1998	Cycling 1 × 20 s max sprint	8 active but untrained M	30 g/d × 3-d	No change to measurement of power. Significant ↑ BM ~1 kg
Odland et al. 1997	Cycling 30 s Wingate test	9 active but untrained M	20 g/d × 3-d	No effect on any recorded exercise measures
Burke et al. 1996	Swimming 25 m, 50 m, 100 m swim, 10 s maximal leg ergometry test	32 national & international swimmers M & F	20 g/d × 5-d	No significant differences between group means for sprint times or 10 s maximal leg ergometry power & work.
Mujika et al. 1996	Swimming 3 × 25 m 3 × 50 m 3 × 100 m	20 national & international swimmers M & F	20 g/d × 5-d	No significant effect on performance. Significant ↑ BM 0.7 kg

Abbreviations: M = Male; F = Female; n.s = non-significant; RM = Repetition maximum; MVC = Maximal volitional contractions; BM = Body mass; FFM = Fat free mass; rec = Recovery

health status in 98 athletes. A loading phase of 15.75 g· day^{-1} for 5-d was followed by a maintenance dose averaging 5 g· day^{-1} thereafter, with a comprehensive urinary and blood chemistry panel determined. The results indicate that long-term CrS (up to 21 months) does not appear to adversely affect markers of health status in athletes undergoing intense training in comparison to athletes who do not take CrS (Kreider et al., 2003). The only significant side effect reported in the literature is that of weight gain within the first few days (Mujika et al., 1996; Kreider et al., 1998; Pearson et al., 1999; Volek et al., 1999; ACSM, 2000; Biwer et al. 2003), which is likely due to water retention related to creatine uptake in the muscle.

CONCLUSION

This review has discussed some of the actions of CrS on muscle metabolism and exercise performance. The available research indicates that CrS can increase muscle PCr content, but not in all individuals, which may improve performance involving short periods of extremely powerful activity, especially during repeated bouts. However, not all studies have reported ergogenic benefit, possibly due to differences in subject response to CrS, length of supplementation, exercise criterion evaluated, and/or the amount of recovery observed during repeated bouts of exercise. It does not appear that CrS increases maximal isometric strength, the rate of maximal force production, nor aerobic exercise performance. Therefore, at this point in time CrS appears to be a safe nutritional strategy that may enhance exercise performance in sports participants requiring maximal single effort and/or repetitive sprint bouts. However, further research should focus on gaining a better understanding of the mechanisms of action that elevated Cr stores have on energetics and metabolism.

REFERENCE

American College of Sports Medicine. (2000) Roundtable on the physiological and health effects of oral creatine supplementation. *Medicine and Science in Sports and Exercise* **32,** 706-717.

Anderson, O. (1993) Creatine propels British athletes to Olympic gold medals: Is creatine the one true ergogenic aid? *Running Research News* **9,** 1-5.

Barnett, C., Hinds, M. and Jenkins, D.G. (1995) Effects of oral creatine loading on multiple sprint cycle performance. *Australian Journal of Science and Medicine in Sports* **28,** 35-39.

Becque, M.D., Lochmann, J.D. and Melrose, D.R. (2000) Effects of oral creatine supplementation on muscular strength and body composition. *Medicine and Science in Sports and Exercise* ***32,*** 654-658.

Biwer, C.J., Jensen, R.L., Schmidt, W.D. and Watts, P.B. (2003) The effect of creatine on treadmill running with high-intensity intervals. *Journal of Strength and Conditioning Research* **17,** 439-445.

Bamberger M. (1998) The magic potion. *Sports Illustrated* **88,** 58-61.

Burke, L.M., Pyne, D.B. and Telford, R.D. (1996) Effect of oral creatine supplementation on single-effort sprint performance in elite swimmers. *International Journal of Sports Nutrition* **6,** 222-233.

Chanutin, A. (1926) The fate of creatine when administered to man. *Journal of Biochemistry* **67,** 29-41.

Dawson, B., Cutler, M., Moody, A., Lawerence, S., Goodman, C. and Randall, N. (1995) Effects of oral creatine loading on single and repeated maximal short sprints. *Australian Journal of Science and Medicine in Sports* **27,** 56-61.

Delecluse, C., Diels, R. and Goris, M. (2003) Effect of Creatine Supplementation on Intermittent Sprint Running Performance in Highly Trained Athletes. *Journal of Strength and Conditioning Research* **17,** 446-454.

Deutekom, M.J., Beltman, G.M., De Ruiter, C.J., De Koning J.J. and De Haan, A. (2000) No acute effects of short-term creatine supplementation on muscle properties and sprint performance. *European Journal of Applied Physiology* **82,** 23-229.

Finn, J.P., Ebert, T.R., Withers, R.T., Carey, M.F., Mackay, M., Phillips, J.W. and Febbraio, M.A. (2001) Effect of creatine supplementation on metabolism and performance in humans during intermittent sprint cycling. *European Journal of Applied Physiology* **84,** 238-243.

Francaux, M. and Poortmans, J.R. (1999) Effects of training and creatine supplement on muscle strength and body mass. *European Journal of Applied Physiology and Occupational Physiology* **80,** 165-168.

Gilliam, J.D., Hohzorn, C., Martin, D. and Trimble, M.H. (2000) Effect of oral creatine supplementation on isokinetic torque production. *Medicine and Science in Sports and Exercise* **32,** 993-996.

Greenhaff, P.L. (1997) The nutritional biochemistry of creatine. *Nutritional Biochemistry* **8,** 610-618.

Greenhaff, P.L., Bodin, K., Soderlund, K. and Hultman, E. (1994) Effect of oral creatine supplementation on skeletal muscle phosphocreatine resynthesis. *American Journal of Physiology Endocrinology and Metabolism* **266,** E725-E730.

Harris, R.C., Soderlund, K. and Hultman, E. (1992) Elevation of creatine in resting and exercised muscle of normal subjects by creatine supplementation. *Clinical Science* **83,** 367-373.

Hultman, E., Soderlund, K., Timmons, J.A., Cederblad, G. and Greenhaff, P.L. (1996) Muscle creatine loading in men. *Journal of Applied Physiology* **81,** 232-237.

International Olympic Committee. (2003) *Prohibited classes of substances and prohibited methods.* Available from URL:

http://www.olympic.org/uk/utilities/reports/level2_uk.asp?HEAD2=1&HEAD1=1

Izquierdo, M., Ibanez, J., Gonzalez-Badillo, J.J. and Gorostiaga, E.M. (2002) Effects of creatine supplementation on muscle power, endurance, and sprint performance. *Medicine and Science in Sports and Exercise* **34,** 332-343.

Jacobs, I. (1999) Dietary creatine monohydrate supplementation. *Canadian Journal of Applied Physiology* **24,** 503-514.

Jacobs, I., Bleue, S. and Goodman, J. (1997) Creatine ingestion increases anaerobic capacity and maximum accumulated oxygen deficit. *Canadian Journal of Applied Physiology* **22,** 231-243.

Kreider, R.B., Ferreira, M., Wilson, M., Grindstaff, P., Plisk, S., Reinardy, J., Cantler, E. and Almada, A.L. (1998) Effects of creatine supplementation on body composition, strength, and sprint performance *Medicine and Science in Sports and Exercise* **30,** 73-82.

Kreider, R.B., Melton, C., Rasmussen, C.J., Greenwood, M., Lancaster, S., Cantler, E.C., Milnor, P. and Almada, A.L. (2003) Long-term creatine supplementation does not significantly affect clinical markers of health in athletes. *Molecular and Cellular Biochemistry* **244,** 95-104.

Kurosawa, Y., Hamaoka, T., Katsumura, T., Kuwamori, M., Kimura, N., Sako, T. and Chance, B. (2003) Creatine supplementation enhances anaerobic ATP synthesis during a single 10 sec maximal handgrip exercise. *Molecular and Cellular Biochemistry* **244,** 105-112.

Lemon, P.W.R. (2002) Dietary creatine supplementation and exercise performance: Why inconsistent results? *Canadian Journal of Applied Physiology* **27,** 663-680.

Louis, M., Poortmans, J.R., Francaux, M., Berre, J., Boisseau, N., Brassine, E., Cuthbertson, D.J., Smith, K., Babraj, J.A., Waddell, T. and Rennie, M.J. (2003) No effect of creatine supplementation on human myofibrillar and sarcoplasmic protein synthesis after resistance exercise. *American Journal of Physiology Endocrinology and Metabolism* **285,** E1089-1094.

McKenna, M.J., Morton, J., Selig, S.E. and Snow, R.J. (1999) Creatine supplementation increases muscle total creatine but not maximal intermittent exercise performance *Journal of Applied Physiology* **87,** 2244-2252.

Meir, R. (1995) Practical application of oral creatine supplementation in professional rugby league: A case study. *Australian Strength and Conditioning Coach* **3,** 6-10.

Metzl, J.D., Small, E., Levine, S.R. and Gershel, J.C. (2001) Creatine use among young athletes. *Pediatrics* **108,** 421-425.

Mommaerts, W.F. (1969) Energetics of muscular contraction. *Physiological Reviews* **49,** 427-508.

Mujika, I., Chatard, J.C., Lacoste, L., Barale, F. and Geyssant, A. (1996) Creatine supplementation does not improve sprint performance in competitive swimmers. *Medicine and Science in Sports and Exercise* **28,** 1435-1441.

Mujika, I. and Padilla, S. (1997) Creatine supplementation as an ergogenic acid for sports performance in highly trained athletes: a critical review. *International Journal of Sports Medicine* **18,** 491-496.

Mujika, I., Padilla, S., Ibanez, J., Izquierdo, M. and Gorostiaga, E. (2000) Creatine supplementation and sprint performance in soccer players. *Medicine and Science in Sports and Exercise* **32,** 518-525.

Odland, L.M., MacDougall, J.D., Tarnopolsky, M.A., Elorriaga, A. and Borgmann, A. (1997) Effect of oral creatine supplementation on muscle [PCr] and short-term maximum power output. *Medicine and Science in Sports and Exercise* **29,** 216-219.

Pearson, D.R., Hamby, D.G., Russel, W. and Harris, T. (1999) Long-term effects of creatine monohydrate on strength and power. *Journal of Strength and Conditioning Research* **13,** 187-192.

Schnedeider, D.A., McDonough, P.P., Fadel, P.J. and Berwick, J.P. (1997) Creatine supplementation and total work performed during 15-s and 1-min bouts of maximal cycling. *Australian Journal of Science and Medicine in Sports* **29,** 65-68.

Smith, S.A., Montain, S.J., Matott, R.P., Zientara, G.P., Jolesz, F.A. and Fielding, R.A. (1998) Creatine supplementation and age influence muscle metabolism during exercise. *Journal of Applied Physiology* **85,** 1349-1356.

Smith, S.A., Montain, S.J., Matott, R.P., Zientara, G.P., Jolesz, F.A. and Fielding, R.A. (1999) Effects of creatine supplementation on the energy cost of muscle contraction: a ^{31}P-MRS study. *Journal of Applied Physiology* **87,** 116-123.

Snow, R.J., McKenna, M.J., Selig, S.E., Kemp, J., Stathis, C.G. and Zhao, S. (1998) Effect of creatine supplementation on sprint exercise performance and muscle metabolism. *Journal of Applied Physiology* **84,** 1667-1673.

Stout, J., Eckerson, J., Ebersole, K., Moore, G., Perry, S., Housh, T., Bull, A., Cramer, J. and Batheja, A. (2000) Effect of creatine loading on neuromuscular fatigue threshold. *Journal of Applied Physiology* **88,** 109-112.

Syrotuik, D.J., Game, A.B., Gillies, E.M. and Bell, G.J. (2001) Effects of creatine monohydrate supplementation during combined strength and high intensity rowing training on performance. *Canadian Journal of Applied Physiology* **26,** 527-542.

Vandenberghe, K., Goris, M., Van Hecke, P.M., Leemputte, V., Vangerven, L. and Hespel, P. (1997) Long-term creatine intake is beneficial to muscle performance during resistance training. *Journal of Applied Physiology* **83,** 2055-2063.

Volek, J.S. and Kraemer, W.J. (1996) Creatine supplementation: Its effect on human muscular performance and body composition. *Journal of Strength and Conditioning Research* **10,** 200-210.

Volek, J.S., Boetes, M., Bush, J.A., Putukian, M., Sebastianelli, W.J. and Kraemer, W.J. (1997a) Response of testosterone and cortisol concentrations to high-intensity resistance exercise following creatine supplementation. *Journal of Strength and Conditioning Research* **11,** 182-187.

Volek, J.S., Kraemer, W.J., Bush, J.A., Boetes, M., Incledon, T., Clark, K.L. and Lynch, J.M. (1997b) Creatine supplementation enhances muscular performance during high-intensity resistance exercise. *Journal of the American Dietetic Association* **97,** 765-770.

Volek, J.S., Duncan, N.D., Mazzetti, S.A., Staron, R.S., Putukian, M., Gomez, A.L., Pearson, D.R., Fink, W.J. and Kraemer, W.J. (1999) Performance and muscle fibre adaptations to creatine supplementation and heavy resistance training. *Medicine and Science in Sports and Exercise* **31,** 1147-1156.

Wilder, N., Deivert, R.G., Hagerman, F. and Gilders, R. (2001) The effects of low-dose creatine supplementation versus creatine loading in collegiate football players. *Journal of Athletic Training* **36,** 124-129.

Williams, M.H. and Branch, J.D. (1998) Creatine supplementation and exercise performance: An update. *Journal of the American College of Nutrition* **17,** 216-234.

Williams, M.H., Kreider, R.B. and Branch, J.D. (1999) *Creatine: The Power Supplement*. Human Kinetics, Champaign, IL.

Wyss, M. and Kaddurah-Daouk, R. (2000) Creatine and creatinine metabolism. *Physiological Reviews* **80,** 1107-1213.

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