Molecular and Cellular Biochemistry **244:** 89–94, 2003.

Effects of creatine supplementation on performance and training adaptations

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Abstract

Creatine has become a popular nutritional supplement among athletes. Recent research has also suggested that there may be a number of potential therapeutic uses of creatine. This paper reviews the available research that has examined the potential ergogenic value of creatine supplementation on exercise performance and training adaptations. Review of the literature indicates that over 500 research studies have evaluated the effects of creatine supplementation on muscle physiology and/or exercise capacity in healthy, trained, and various diseased populations. Short-term creatine supplementation (e.g. 20 g/day for 5–7 days) has typically been reported to increase total creatine content by 10–30% and phosphocreatine stores by 10–40%. Of the approximately 300 studies that have evaluated the potential ergogenic value of creatine supplementation, about 70% of these studies report statistically significant results while remaining studies generally report non-significant gains in performance. No study reports a statistically significant ergolytic effect. For example, short-term creatine supplementation has been reported to improve maximal power/strength (5–15%), work performed during sets of maximal effort muscle contractions (5–15%), single-effort sprint performance (1–5%), and work performed during repetitive sprint performance (5–15%). Moreover, creatine supplementation during training has been reported to promote significantly greater gains in strength, fat free mass, and performance primarily of high intensity exercise tasks. Although not all studies report significant results, the preponderance of scientific evidence indicates that creatine supplementation appears to be a generally effective nutritional ergogenic aid for a variety of exercise tasks in a number of athletic and clinical populations. (Mol Cell Biochem **244**: 89–94, 2003)

Key words: sport nutrition, ergogenic aids, exercise, training, phosphocreatine

Introduction

An ergogenic aid is a technique or practice that serves to increase performance capacity, the efficiency to perform work, the ability to recover from exercise, and/or the quality of training thereby promoting greater training adaptations. [1] When evaluating the potential ergogenic value of a proposed aid, it is important to evaluate the theoretical rationale, the scientific evidence that the proposed aid affects exercise metabolism and/or performance, whether studies have incorporated an appropriate research design (e.g. double blind, placebo controlled, randomized clinical trial), and the reliability of the experimental methods employed. It is also important to examine whether a proposed ergogenic aid is safe for a given population. Based on a thorough analysis of the literature, it is then possible to make conclusions regarding the ergogenic value and safety of a proposed aid [1].

In the case of creatine, it has been well established that increasing dietary availability of creatine serves to increase total creatine (TC) and phosphocreatine (PC) concentrations in the muscle [2–9]. Moreover, that availability of creatine and PC play a significant role in contributing to energy metabolism particularly during intense exercise. For example, creatine supplementation (e.g. 20 g/day × 5 days) has been reported to increase muscle TC and PC typically by 15–40% [10–12]. Theoretically, increasing the availability of PC would enhance cellular bioenergetics of the phosphagen system that is involved in high-intensity exercise performance [7, 11, 13] as well as the shuttling of high-energy phosphates between the mitochondria and cytosol via the creatine phosphate shut-

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tle that may enhance both anaerobic and aerobic capacity [14, 15].

Over the last several years, a number of reviews were published examining the potential ergogenic value of creatine supplementation [6, 7, 10–13, 16–19]. These reviews generally concluded that creatine supplementation serves to increase muscle TC and PC content. In addition, that creatine may improve performance primarily during short-duration, high intensity exercise. However, there was less evidence that creatine supplementation enhanced exercise performance during moderate to high-intensity prolonged exercise. In addition, there were some questions whether results observed in laboratory settings would transfer to performance on the field, whether performance changes observed would enhance training adaptations, and whether long-term creatine supplementation was safe. Since these reviews, a number of research studies have been published evaluating the effects of creatine supplementation on performance and training adaptations in a variety of populations. The purpose of this paper is to examine the most recent research that has examined the effects of short-term creatine supplementation on exercise performance and whether creatine supplementation during training can serve as a safe and effective ergogenic aid for athletes.

Effects of short-term creatine supplementation on performance

Numerous studies have examined the effects of short-term creatine supplementation (5–7 days) on exercise performance. As described in a number of reviews, the majority of initial studies suggested that creatine supplementation can significantly increases strength, power, sprint performance, and/or work performed during multiple sets of maximal effort muscle contractions [6, 7, 10–13, 16, 20]. More recent studies have supported these initial observations. For example, Volek *et al*. [21] reported that creatine supplementation (25 g/day for 7 days) resulted in a significant increases in the amount of work performed during five sets of bench press and jump squats in comparison to a placebo group. Urbanski *et al*. [22] reported that creatine supplementation (20 g/day × 5 days) increased maximal isometric knee extension strength and time to fatigue. Tarnopolsky *et al*. [23] reported creatine supplementation (20 g/day × 4 days) increased peak cycling power, dorsi-flexion maximal voluntary contractions (MVC) torque, and lactate in men and women with no apparent gender effects. Moreover, Wiroth *et al*. [24] reported that creatine supplementation (15 g/day × 5 days) significantly improved maximal power and work performed during 5 × 10-sec cycling sprints with 60-sec rest recovery in younger and older subjects. These findings and many others support prior reports indicating that creatine supplementation can improve performance when evaluated in controlled laboratory and testing settings.

Some have criticized this type of early creatine research suggesting that although performance gains have been observed in controlled laboratory settings, it was less clear whether these changes would improve athletic performance on the field [17, 19]. Since then, a number of studies have attempted to evaluate the effects of creatine supplementation on field performance. These studies have generally indicated that short-term creatine supplementation may improve high intensity, short-duration performance in various athletic tasks. For example, Skare *et al*. [25] reported that creatine supplementation (20 g/day) decreased 100-m sprint times and reduced the total time of 6 × 60-m sprints in a group of well-trained adolescent competitive runners. Mujika *et al*. [26] reported that creatine supplementation (20 g/day × 6 days) improved repeated sprint performance (6 × 15 m sprints with 30-sec recovery) and limited the decay in jumping ability in 17 highly trained soccer players. Similarly, Theodorou *et al*. [27] reported that creatine supplementation (25 g/day × 4 days) significantly improved mean interval performance times in 22 elite swimmers. These recent preliminary findings and many others suggest that creatine supplementation can improve performance of athletes in a variety of sport-related field activities [28–41].

Since creatine supplementation may affect shuttling of high-energy phosphates between the cytosol and mitochondria, some have suggested that creatine supplementation may affect performance during more prolonged exercise bouts. Recent studies also provide some support this contention. For example, Earnest *et al*. [42] reported that creatine supplementation (20 g/day × 4 days and 10 g/day × 6 days) improved cumulative run time to exhaustion in two runs lasting approximately 90-sec each. Smith *et al*. [43] reported that creatine supplementation (20 g/day × 5 days) increased work rate during exercise bouts lasting between 90–600 sec primarily at the shorter, more intense exercise bouts. Nelson *et al*. [44] found that creatine supplementation (20 g/day × 7 days) decreased submaximal heart rate and oxygen uptake (VO_2), while increasing ventilatory anaerobic threshold (VANT) and total time to exhaustion during a maximal exercise test in 36 trained adults. Rico-Sanz *et al*. [45] reported that creatine supplementation (20 g/day × 5 days) increased time to exhaustion (29.9 ± 3.8 to 36.5 ± 5.7 min) while reducing ammonia levels (a marker of adenine nucleotide degradation) when cycling at 30 and 90% of maximum until exhaustion. Finally, Preen *et al*. [46] evaluated the effects of ingesting creatine (20 g/day × 5 days) on resting and post-exercise TC and PC as well as performance of an 80-min intermittent sprint test (10 sets of 5–6 × 6-sec sprints with varying recovery intervals). The authors reported that creatine increased resting and post-exercise TC and PC, mean work performed, and total work performed during 6 × 6-sec sets with 54- and 84-sec recovery. In addition, work performed during 5 × 6-sec sprints with 24-sec recovery tended to be greater ($p = 0.056$). Collectively, these findings support contentions that creatine supplementation may provide ergogenic benefit for more prolonged exercise bouts involving both anaerobic and aerobic energy systems.

However, as with previous creatine research, not all of the recent studies have found that creatine supplementation enhances exercise performance. For example, McKenna *et al.* [47] reported that creatine supplementation (30 g/day × 5 days) did not affect 5 × 10-sec sprints with rest intervals of 180, 50, and 20-sec in 14 untrained subjects. Gilliam *et al.* [48] found that creatine supplementation (20 g/day × 5 days) did not affect isokinetic knee extension performance during 5 × 30 MVC in 23 untrained subjects. Deutekom *et al.* [49] reported that creatine (20 g/day × 6 days) increased body mass but did not affect muscle activation, fatigue, and/or recovery from electrical stimulation of the quadriceps or maximal exercise performance during sprint cycling in 23 well-trained rowers. Similarly, Edwards *et al.* [50] reported that creatine (20 g/day × 6 days) did not affect running fatigue to exhaustion following performing 4 × 15-sec sprints in 21 moderately active subjects. However, ammonia levels were lower following creatine supplementation suggesting that may have lessened the degree of adenine nucleotide degradation and improved metabolic efficiency. In another study, Op't Eijnde *et al.* [51] reported that creatine (20 g/day × 5 days) did not enhance stroke performance or 70-m agility sprint performance in well-trained tennis players. Finally, Finn *et al.* [2] reported that although creatine supplementation (20 g/day × 5 days) increased TC content and 1-sec relative peak power in 16 triathletes, no significant effects were observed in repetitive cycling sprint performance (4 × 20-sec sprints with 20-sec rest recovery).

In my view, when one examines all of the available literature on creatine supplementation, the following conclusions can be drawn. First, although some intra-subject variability has been reported, the vast majority of studies available to date (> 90%) indicate that short-term creatine supplementation significantly increases TC and PC content as determined by assessing muscle biopsies, urinary whole body creatine retention, and/or magnetic resonance spectroscopy (MRS) [4, 6, 9, 10, 12, 52, 53]. Consequently, it is clear that creatine supplementation enhances the potential to perform high intensity exercise much like carbohydrate loading enhances the potential to perform endurance exercise to exhaustion. Overall, approximately 70% of short-term studies on creatine supplementation report some ergogenic benefit particularly during high- intensity, repetitive exercise [10, 12]. These benefits have been primarily found when performing laboratory tests that have good test-to-test reliability [23]. However, as described above, a number of recent studies have indicated that creatine supplementation can also improve performance in field type events like running, soccer, and swimming. It is also interesting to note that over the last few years, the percentage of studies reporting ergogenic benefit from creatine supplementation has risen to 80–85% presumably due to a greater understanding of how to properly design studies to assess the ergogenic value of creatine supplementation. Benefits have been reported in untrained, trained, and diseased children, adolescents, adults, and elderly populations [10, 12, 54]. Studies reporting no significant effects of creatine supplementation have generally observed small but non-significant improvements in performance (i.e. 1–7%). It should be noted that no study has reported a statistically significant ergolytic (negative) effect from creatine supplementation. Studies that have reported no significant benefit of creatine supplementation often have low statistical power, have evaluated performance tests with large test-to-test reliability, and/or have not incorporated appropriate experimental controls. Consequently, it is my view that the preponderance of evidence indicates that short-term creatine supplementation enhances performance in a variety of laboratory and on-field exercise tasks.

Effects of creatine supplementation on training adaptations

Theoretically, increasing the ability to perform high-intensity exercise may lead to greater training adaptations over time. Consequently, a number of studies have evaluated the effects of creatine supplementation on training adaptations. For example, Vandenberghe *et al.* [55] reported that in comparison to a placebo group, creatine supplementation (20 g/day × 4 days; 5 g/day × 65 days) during 10-weeks of training in women increased TC and PC, maximal strength (20–25%), maximal intermittent exercise capacity of the arm flexors (10–25%), and fat free mass (FFM) by 60%. In addition, the researchers reported that creatine supplementation during 10-weeks of detraining helped maintain training adaptations to a greater degree. Kelly *et al.* [56] reported that 26-days of creatine supplementation (20 g/day × 4 days; 5 g/day × 22 days) significantly increased body mass, FFM, three repetition maximum (RM) on the bench press, and the number of repetitions performed in the bench press over a series of sets in 18 power lifters. Noonan *et al.* [57] reported that creatine supplementation (20 g/day × 5 days; 100 or 300 mg/kg/day of FFM × 51 days) in conjunction with resistance and speed/agility training significantly improved 40-yard dash time and bench press strength in 39 college athletes. Kreider *et al.* [58] reported that creatine supplementation (15.75 g/day × 28 days) during off-season college football training promoted greater gains in FFM and repetitive sprint performance in comparison to subjects ingesting a placebo. Likewise, Stone *et al*. [38] reported that 5-weeks of creatine ingestion (~ 10 or 20 g/day with and without pyruvate) promoted significantly greater increases in body mass, FFM, 1 RM bench press, combined 1 RM squat and bench press, vertical jump power output, and peak rate of force development during in-season training in 42 Division IAA college football players.

Volek *et al*. [8] reported that 12-weeks of creatine supplementation (25 g/day × 7 days; 5 g/day × 77 days) during periodized resistance training increased muscle TC and PC, FFM, type I, IIa, and IIb muscle fiber diameter, bench press and squat 1 RM, and lifting volume (weeks 5–8) in 19 resistance trained athletes. Peters *et al*. [59] reported that creatine monohydrate and creatine phosphate supplementation (20 g/day × 3 days; 10 g/day × 39 days) during training significantly increased body mass, FFM, and 1-RM bench press in 35 resistance-trained males. Kirksey *et al*. [60] found that creatine supplementation (0.3 g/kg/day × 42 days) during off-season training promoted greater gains in vertical jump height and power, sprint cycling performance, and FFM in 36 Division IAA male and female track and field athletes. Pearson *et al*. [61] reported that creatine supplementation (5 g/day × 10 weeks) during resistance training promoted greater gains in strength, power, and body mass with no change in percent body fat in 16 Division IA college football players during summer conditioning. Moreover, Jones *et al*. [32] reported that creatine (20 g/day × 5 days; 5 g/day × 10 weeks) promoted greater gains in sprint performance (5 × 15-sec with 15-sec recovery) and average on-ice sprint performance (6 × 80-m sprints) in 16 elite ice-hockey players. Becque *et al*. [62] found that creatine supplementation (20 g/day × 5 days; 2 g/day × 37 days) during strength training led to greater gains in arm flexor muscular strength, upper arm muscle area, and FFM than strength training alone in 23 resistance trained athletes.

Additionally, Burke *et al*. [63] reported that low dose creatine supplementation (7.7 g/day × 21 days) during training promoted greater gains in total work until fatigue, peak force, peak power, and fatigue resistance in 41 college athletes. Brenner *et al*. [64] reported that creatine supplementation (20 g/day × 7 days; 2 g/day × 28 days) significantly improved upper-body strength gain and decreased percent body fat in 16 female college lacrosse players during pre-season training. Larson-Meyer *et al*. [34] reported that creatine supplementation (15 g/day × 7 days; 5 g/day × 84 days) promoted greater gains in bench press and squat maximal strength with no differences in FFM during off-season training in 14 female college soccer players. Interestingly, Jowko *et al*. [65] recently reported that creatine supplementation (20 g/day × 7 days; 10 g/day × 14 days) significantly increased FFM and cumulative strength gains during training in 40 subjects initiating training. Additional gains were observed when 3 g/day of calcium beta-hydroxy-beta-methylbutyrate (HMB) was co-ingested with creatine.

In a very interesting experimental design, Stevenson *et al*. [66] evaluated the effects of creatine supplementation (20 g/day × 7 days; 5 g/day × 49 days) on volitional and electrical stimulated training in 18 resistance trained subjects. Subjects participated in a traditional resistance training program as well as an electromyostimulation (EMS) training program (i.e. 3–5 sets × 10 eccentric and concentric contractions performed twice per week on one leg). The researchers found that creatine supplementation did not affect mechanical or hypertrophic responses to the EMS training. However, magnetic resonance imaging (MRI) determined cross-sectional area of the traditionally trained but non-electrically stimulated leg was significantly greater in the creatine group. Finally, Willougby *et al*. [9] recently reported that in comparison to controls, creatine supplementation (6 g/day × 12 weeks) during resistance training (6–8 repetitions at 85–90%; 3 × weeks) significantly increased total body mass, FFM, and thigh volume, 1 RM strength, myofibrillar protein content, Type I, IIa, and IIx myosin heavy chain (MHC) mRNA expression, and MHC protein expression. This study provides strong evidence that creatine supplementation during intense resistance training leads to greater gains in strength and muscle mass.

In my view, after evaluating the available data on the effects of creatine supplementation on training adaptations, the following conclusions can be drawn. Studies that evaluated the effects of creatine supplementation on muscle TC and PC stores described in the present review as well as the majority of previous studies reviewed elsewhere indicate that creatine loading increases TC and PC. Creatine supplementation during training is typically associated with a 0.5–2 kg greater increase in body mass and/or FFM. Although it has been hypothesized that the initial weight gain associated with creatine supplementation may be due to fluid retention, a number of studies indicate that long-term creatine supplementation increases FFM and/or muscle fiber diameter with no disproportional increase in total body water. These findings suggest that the weight gain observed during training appears to be muscle mass. About 90% of long-term training studies report some ergogenic benefit with gains typically 10–100% greater than controls. Improvements have been reported in untrained and trained adolescents, adults, and elderly populations. No clinically significant side effects have been reported in these studies even though many of them involved intense training in a variety of exercise conditions. These findings suggest that creatine supplementation during training serves to enhance training adaptations. Moreover, these beneficial changes may offer some therapeutic benefit for a variety of pathologies involving muscle weakness and/or muscle wasting.

Conclusions

Creatine appears to be an effective and safe nutritional ergogenic aid to improve high intensity exercise performance and/or training adaptations in a variety of sports. Although more research on the potential ergogenic value of creatine for specific athletic populations may be useful, it is my view that the most promising area of future research will be to examine potential therapeutic benefit for various clinical populations.

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