Journal of Strength and Conditioning Research, 2003, 17(4), 822–831

Brief Review

Effects of Creatine Supplementation and Resistance Training on Muscle Strength and Weightlifting Performance

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ABSTRACT

Creatine monohydrate has become the supplement of choice for many athletes striving to improve sports performance. Recent data indicate that athletes may not be using creatine as a sports performance booster per se but instead use creatine chronically as a training aid to augment intense resistance training workouts. Although several studies have evaluated the combined effects of creatine supplementation and resistance training on muscle strength and weightlifting performance, these data have not been analyzed collectively. The purpose of this review is to evaluate the effects of creatine supplementation on muscle strength and weightlifting performance when ingested concomitant with resistance training. The effects of gender, interindividual variability, training status, and possible mechanisms of action are discussed. Of the 22 studies reviewed, the average increase in muscle strength (1, 3, or 10 repetition maximum [RM]) following creatine supplementation plus resistance training was 8% greater than the average increase in muscle strength following placebo ingestion during resistance training (20 vs. 12%). Similarly, the average increase in weightlifting performance (maximal repetitions at a given percent of maximal strength) following creatine supplementation plus resistance training was 14% greater than the average increase in weightlifting performance following placebo ingestion during resistance training (26 vs. 12%). The increase in bench press 1RM ranged from 3 to 45%, and the improvement in weightlifting performance in the bench press ranged from 16 to 43%. Thus there is substantial evidence to indicate that creatine supplementation during resistance training is more effective at increasing muscle strength and weightlifting performance than resistance training alone, although the response is highly variable.

Key Words: creatine monohydrate, strength training, nutritional supplement, ergogenic aid, phosphocreatine

Reference Data: Rawson, E.S., and J.S. Volek. Effects of creatine supplementation and resistance training on muscle strength and weightlifting performance. *J. Strength Cond. Res. 17(4):822–831. 2003.*

Introduction

Since 1993, over 200 studies examining the effects of creatine supplementation on exercise performance have been published, and in a consensus statement the American College of Sports Medicine (ACSM; 53) concluded that, ''exercise performance involving short periods of extremely powerful activity can be enhanced, especially during repeated bouts. . . '' by creatine supplementation. Thus, under the right conditions, creatine supplementation can be an effective performance enhancer (53). However, it could be argued that athletes are not using creatine as a performance booster per se but instead use creatine as a training aid during periods of intense resistance training (18, 25, 28, 42, 43). The ACSM consensus also states ''creatine supplementation is associated with enhanced accrual of strength in strength-training programs.'' Athletes hope that ingesting creatine concurrent with progressive resistance training, and over prolonged periods of time, will augment their workouts, resulting in increased muscle strength and improved weightlifting performance (maximal repetitions at a given percent of maximal strength) in the weight room. The assumption is that the ''benefits'' acquired with the assistance of creatine in the weight room will translate into improved performance on the playing field.

Although several studies have evaluated the combined effects of creatine supplementation and resistance training on muscle strength and weightlifting performance, and athletes are reportedly ingesting creatine chronically during progressive resistance training programs, these data have not been analyzed collectively. With that in mind, it is the purpose of this review to evaluate the effects of creatine supplementation on muscle strength and weightlifting performance in young healthy men and women when ingested concomitant with resistance training.

Prevalence of Creatine Supplementation

In recent years creatine monohydrate has become the supplement of choice for many athletes who are striving to increase strength, gain weight, or enhance sports performance. Recent surveys indicate that creatine use ranges from 28 to 41% in the National Collegiate Athletic Association (NCAA), and that athletes from 17 different NCAA sports reportedly use creatine (18, 28). A survey of 229 members of military or civilian health clubs conducted by Sheppard et al. (42) reported that 29–57% (military vs. civilian) of members are creatine users. Creatine use in power sport athletes may be even more prevalent, with 45 to 74% of powerlifters, boxers, weightlifters, and track and field athletes reportedly using the supplement (41, 43). Creatine use is not limited to adults; adolescents are using creatine supplements as well. In a survey of 37 public high schools in Wisconsin, McGuine et al. (30) reported that 16.7% of high school student-athletes use creatine, and that creatine use increases throughout high school (9th grade, 8.4% creatine users; 12th grade, 24.6% creatine users). In high school football players, 30% of survey respondents reported creatine use, and, as when all high school sports are combined, the pattern of increased creatine use throughout high school persisted in football as well (9th grade, 10.4% creatine users; 12th grade, 50.5% creatine users; 31).

Sheppard et al. (42) reported that periods of creatine use averaged 40 weeks in health club members. Stanton and Abt (43) reported creatine supplementation protocols ranging from 4 to 56 days (loading phase) and from 14 to 91 days (maintenance phase) in powerlifters. Juhn et al. (25) surveyed 52 NCAA athletes (aged 18–23 years) and reported that baseball and football players ingest creatine for 5 and 3 months, respectively, and most often ingest it in the off-season. This is the time of year when athletes spend the most time performing progressive resistance training in an attempt to increase strength and/or body mass for the upcoming competitive season. When surveyed about the perceived benefits of creatine ingestion, athletes often cited increased strength (46–92%), increased muscle size (55–85%), weight gain (27–47%), and quicker recovery (81%; 18, 28, 42, 43). Thus, there is evidence that athletes are not ingesting creatine acutely to directly improve sports performance, but are instead using the supplement chronically in an effort to increase muscle strength, muscle size, and body mass during training.

Article Inclusion Criteria

The inclusion criteria for studies in this review were as follows: (a) subjects must have ingested creatine while participating in resistance training; and (b) muscle strength on a weightlifting task (e.g., 1RM squat, 3RM bench press, etc.) and/or weightlifting performance (e.g., number of bench press repetitions at 80% 1RM) had to be reported; and (c) there was a placebo group that performed the same resistance training program. One study that compared 2 groups matched on supplemental carbohydrate and nitrogen intake (creatine plus carbohydrate vs. protein plus carbohydrate) was excluded (52), and 1 study that only provided change scores (27) was included in the table for the reader's benefit, but not in the overall calculations described in this review. There were no restrictions set on the duration of the supplementation regimen, the duration of the resistance training program, the design or volume of the resistance training program, training experience, or gender of the subjects. Studies that investigated the effects of creatine supplementation during resistance training in older subjects were excluded (4, 8), because few data on the benefits of creatine ingestion in older subjects are available and the findings have been discrepant (14, 37–39, 58). From the studies that were included in this review, only data on muscle strength during weightlifting or weightlifting performance are reported. We did not examine the influence of creatine dosage in this review, as it is unlikely that any of the studies included were confounded by providing doses of creatine insufficient to increase muscle creatine stores. As the purpose of this review was to focus on the effects of creatine supplementation and concurrent resistance training on muscle strength and weightlifting performance, exercise performance measures such as those obtained from isokinetic, jumping, or cycling performance tests are not included in this review.

Twenty-two studies met our inclusion criteria (Table 1). The studies ranged from 7 to 91 days and involved only male subjects (17 studies), only female subjects (3 studies), or both male and female subjects (2 studies). Supplementation protocols ranged from 20 to 25 g of creatine per day for the entire supplementation period, loading doses of creatine were for 3–7 days, followed by a maintenance dose for the remainder of the supplementation period and lower doses (5 $g \cdot d^{-1}$, 0.09 $g \cdot kg^{-1} \cdot d^{-1}$) of creatine for the entire supplementation period. The majority of studies used 1RM testing of large muscle group exercises (e.g., bench press and squat) and smaller muscle group exercises (leg extension, arm curls, etc.). Several studies also assessed the number of repetitions performed in a set using a standard weight, such as 70% of the 1RM weight or presupplementation 8RM–10RM weight.

Overall Effect on Muscle Strength and Weightlifting Performance

Of the 22 studies reviewed, 16 reported a significantly ($p < 0.05$) greater improvement in muscle strength and/or weightlifting performance in subjects ingest-

Table 1. Muscle strength and weightlifting performance following creatine or placebo supplementation with concurrent resistance training program.†

Subjects	Supplement duration (d)	Initial training status	Activity during supplementation	Δ Creatine group	Δ Placebo group	Reference
8 M	28	≈11 y resistance training	Maintained current resistance training program (28 d)	6% ↑ in bench press 1RM* ($p < 0.05$ from placebo) 26% ↑ in bench press repetitions (at 70% of 1RM)* * ($p < 0.001$ from placebo)	No change from baseline	(11)
14 M	7	≈6 y resistance training	Maintained current resistance training program (7 d)	30% ↑ in bench press repetitions (at 10RM) over 5 sets	No change from baseline	(56)
19 F	74	Untrained	10-wk resistance training program	43% ↑ in leg press 1RM* 45% ↑ in bench press 1RM 63% ↑ in leg curl 1RM 85% ↑ in leg extension 1RM* 46% ↑ in squat 1RM* 31% ↑ in shoulder press 1RM * ($p < 0.05$ from placebo)	25% ↑ in leg press 1RM 38% ↑ in bench press 1RM 39% ↑ in leg curl 57% ↑ in leg extension 25% ↑ in squat 24% ↑ in shoulder press	(54)
39 M	56	Resistance trained collegiate football players (Division II)	8-wk resistance training program	6% ↑ in bench press 1RM* * ($p < 0.05$ from placebo)	No change from baseline	(33)
25 M	28	Resistance trained collegiate football players (Division IA)	Undergoing winter/spring (off-season) resistance training program (28 d)	225 kg ↑ in bench press lifting volume (weightlifted × repetitions)* ($p < 0.005$ from placebo) 327 kg ↑ in squat lifting volume 1,100 kg ↑ in power clean lifting volume 1,558 kg ↑ in total lifting volume* * ($p = 0.05$ from placebo)	−5 kg ↓ in bench press lifting volume (weightlifted × repetitions) 267 kg ↑ in squat lifting volume 921 kg ↑ in power clean lifting volume 1,105 kg ↑ in total lifting volume	(27)‡
18 M	26	Minimum 2 y resistance training (competitive powerlifters)	Continued precompetition training (26 d)	8% ↑ in bench press 3RM* ($p < 0.001$ from placebo) 39% ↑ in bench press repetitions (at 85% of 1RM) * ($p < 0.001$ from placebo)	2% ↑ in bench press 3RM No change in bench press repetitions (at 85% of 1RM)	(26)
19 M	84	Resistance trained	12-wk resistance training program w/preparatory, hypertrophy, strength, and peaking phases	24% ↑ in bench press 1RM* ($p < 0.05$ from placebo) 32% ↑ in squat 1RM No change in bench press repetitions (at 80% 1RM)	16% ↑ in bench press 1RM 24% ↑ in squat 1RM No change in bench press repetitions (at 80% 1RM)	(55)
16 M	70	Resistance trained collegiate football players (Division IA)	10-wk off-season resistance training w/hypertrophy, strength, and power phases	3% ↑ in bench press 1RM* 11% ↑ in squat 1RM* 6% ↑ in power clean 1RM* ($p < 0.05$ from placebo)	No change from baseline	(35)
35 M	42	Minimum 2 y of resistance training	6-wk periodization resistance training program of only bench press, leg press, and curl exercises (supplemental exercises were permitted)	10% ↑ in bench press 1RM* 12% ↑ in leg press 1RM 106% ↑ in curl repetitions (at 8–10RM) * ($p < 0.01$ from placebo)	1% ↑ in bench press 1RM 10% ↑ in leg press 1RM 96% ↑ in curl repetitions (at 8–10RM)	(36)

Table 1. Continued.

Subjects	Supplement duration (d)	Initial training status	Activity during supplementation	Δ Creatine group	Δ Placebo group	Reference
20 M	35	Resistance trained collegiate football players (Division AA)	5-wk in-season resistance training	10% ↑ in bench press 1RM* 12% ↑ in squat 1RM* 11% ↑ in bench press plus squat 1RM* * ($p < 0.05$ from placebo)	4% ↑ in bench press 1RM 8% ↑ in squat 1RM 6% ↑ in bench press plus squat 1RM	(47)
24 M	56	Resistance trained collegiate football players (at least 3 y) (Division II)	8-wk resistance training program	7% ↑ in bench press 1RM (creatine group) 13% ↑ in bench press 1RM (creatine + CHO group)* * ($p < 0.05$ from CHO group)	5% ↑ in bench press 1RM (CHO group)	(48)
23 M	42	Minimum 1 y of resistance training	6-wk arm flexor training of preacher curls 2 d per week	28% ↑ in preacher curl 1RM* * ($p < 0.01$ from placebo)	16% ↑ in preacher curl 1RM	(2)
21 M	37	≈5 y resistance training	8-wk resistance training program	5 d supplementation group: 9% ↑ in bench press 1RM 17% ↑ in leg press 1RM 16% ↑ in bench press repetitions (at 80% 1RM) 31% ↑ in leg press repetitions (at 80% 1RM)	7% ↑ in bench press 1RM 8% ↑ in leg press 1RM 4% ↑ in bench press repetitions (at 80% 1RM) 16% ↑ in leg press repetitions (at 80% 1RM)	(49)
				37 d supplementation group: 9% ↑ in bench press 1RM 16% ↑ in leg press 1RM 43% ↑ in bench press repetitions (at 80% 1RM) 18% ↑ in leg press repetitions (at 80% 1RM)		(49)
16 F	35	Resistance trained collegiate lacrosse players (Division I)	4.5-wk resistance training program	17% ↑ in bench press 1RM* 3% ↑ in leg extension 1RM * ($p < 0.05$ from placebo)	7% ↑ in bench press 1RM 3% ↑ in leg extension 1RM	(5)
14 F	91	Resistance trained collegiate soccer players (Division IA)	13-wk off-season resistance training program	18% ↑ in bench press 1RM 24% ↑ in squat 1RM	9% ↑ in bench press 1RM 12% ↑ in squat 1RM	(12)
30 M	28	Untrained	4-wk resistance training program	Creatine alone group: 8% ↑ in bench press 1RM 16% ↑ in leg press 1RM Creatine plus training group: 18% ↑ in bench press 1RM 42% ↑ in leg press 1RM* * ($p < 0.01$ from placebo)	9% ↑ in bench press 1RM 16% ↑ in leg press 1RM	(1)
29 M 2 F	7	≈3 y resistance training	Maintained current resistance training program (7 d)	3% ↑ in leg extension 1RM 7% ↑ in leg extension repetitions (at 12–15RM) over 5 sets	1% ↑ in leg extension 1RM 4% ↑ in leg extension repetitions (at 12–15RM) over 5 sets	(46)

Table 1. Continued.

Subjects	Supplement duration (d)	Initial training status	Activity during supplementation	Δ Creatine group	Δ Placebo group	Reference
17 M	63	Resistance trained collegiate football players (at least 3 y) (Division IA)	9-wk preseason periodized resistance training	5% ↑ in bench press 1RM* 4% ↑ in power clean 1RM 9% ↑ in squat 1RM* * ($p < 0.05$ from placebo)	No change in bench press 1RM 2% ↑ in power clean 1RM 5% ↑ in squat 1RM	(3)
16 M	84	Untrained	12-wk resistance training program of only leg press, leg extension, and leg curl	54% ↑ in relative leg press 1RM* * ($p < 0.05$ from placebo)	29% ↑ in relative leg press 1RM	(57)
21 M	21	Untrained	3-wk resistance training program	54% ↑ in leg press 1RM* 11% ↑ in bench press 1RM 16% ↑ in power clean 1RM* 16% ↑ in shoulder press 1RM 14% ↑ in bicep curl 1RM* 14% ↑ in squat 1RM* 17% ↑ in tricep extension 1RM* 15% ↑ in total of all 1RM* * ($p < 0.05$ from placebo)	29% ↑ in leg press 1RM 4% ↑ in bench press 1RM 6% ↑ in power clean 1RM 7% ↑ in shoulder press 1RM 5% ↑ in bicep curl 1RM 3% ↑ in squat 1RM 3% ↑ in tricep extension 1RM 5% ↑ in total of all 1RM	(24)
12 M 10 F	42	Collegiate rowers	6-wk periodized resistance training program and rowing program	5% ↑ in bench press 10RM 22% ↑ in leg press 10RM No change from baseline in mean bench press repetitions over 3 sets (at 10RM) No change from baseline in mean leg press repetitions over 3 sets (at 10RM)	6% ↑ in bench press 10RM 26% ↑ in leg press 10RM No change from baseline in mean bench press repetitions (at 10RM) over 3 sets No change from baseline in mean leg press repetitions over 3 sets (at 10RM)	(50)
36 M	42	≈5 y resistance training	6-wk resistance training program	Creatine plus whey protein group: 17% ↑ in bench press 1RM* 20% ↑ in squat 1RM * ($p < 0.05$ from whey and placebo)	Whey protein group: 7% ↑ in bench press 1RM 17% ↑ in squat 1RM Placebo group: 8% ↑ in bench press 1RM 15% ↑ in squat 1RM	(6)§

* Percent changes listed are significantly different from baseline values, and significant differences between creatine and placebo groups are noted. Data on percent change were calculated from values in text or estimated from graphs where needed. One study (27) only provided change scores in kilograms; these values are reported in place of percent change. M = male; F = female.

† The sample size listed represents the total number of subjects in the placebo and experimental groups, supplement duration refers to the length of the supplement/training period, training status refers to years of resistance training experience (when provided), and activity during supplementation is a brief description of the training program (e.g., intervention, maintenance of current program, single body part design). Only change scores were provided for this study.

§ The whey protein group is included in this analysis to control for the increase in nitrogen intake in the whey plus creatine group.

ing creatine, 1 acute study (7 days) reported significant gains in the creatine group and no change in the placebo group (only within-group statistical tests were conducted; 56), and 5 studies reported no significant difference between creatine and placebo groups (Table 1).

The average increase in muscle strength (1RM, 3RM, 10RM) following creatine supplementation plus resistance training was 20%, whereas the average increase in muscle strength following placebo ingestion during resistance training was 12%. The average increase in weightlifting performance (maximal repetitions at a given percent of maximal strength) following creatine supplementation plus resistance training was 26%, whereas the average increase in weightlifting performance following placebo ingestion during resistance training was 12%. These percentages were calculated as the average percent increase in muscle strength and weightlifting performance with all studies and all exercise tests combined.

These data indicate that individuals ingesting creatine during resistance training will have on average an 8% greater increase in muscle strength than individuals ingesting placebo during resistance training (20 vs. 12%). Additionally, the combined effects of creatine supplementation and resistance training resulted in a 14% difference in weightlifting performance in individuals ingesting creatine during resistance training compared with individuals ingesting placebo during resistance training (26 vs. 12%).

Interindividual Variability

It is noteworthy that there is considerable variability in the change in muscle strength and weightlifting performance in both men and women following a period of creatine supplementation plus resistance training. This can be demonstrated using the bench press, the most frequently tested exercise, as an example. The increase in bench press 1RM in the studies included in this review range from 3 to 45%, and the improvement in weightlifting performance in the bench press (repetitions to muscular failure at a given percent of maximal strength) range from 16 to 43%. A significant portion of the large variability in the change in muscle strength and weightlifting performance following creatine supplementation is likely explained by the large between-subject variability in muscle creatine uptake following creatine supplementation (21). Skeletal muscle creatine is approximately 125 $mmol \cdot kg^{-1}$ dry mass (20), but values ranging from 90 to 180 $mmol \cdot kg^{-1}$ dry mass have been measured (15, 19, 20). Thus, baseline muscle creatine is highly variable, and it is known that high baseline muscle creatine is associated with low muscle creatine uptake (and vice versa; 15, 17, 19). Several factors influence muscle creatine uptake and could also account for the large interindividual variability. When ingested concurrent with creatine supplementation, insulin, carbohydrate, and protein-carbohydrate combined increase muscle creatine accumulation compared with creatine ingestion alone (15, 16, 44, 45). Additionally, creatine supplementation in conjunction with exercise increases muscle creatine uptake in the exercised muscles (21, 40). A low creatine (i.e., vegetarian) diet results in lower urine creatinine levels (10), indirectly indicating that vegetarians have reduced muscle creatine. Recently, it was shown that a 26-day vegetarian diet reduced muscle creatine in omnivores, but muscle creatine following creatine supplementation was similar between subjects following vegetarian and omnivorous diets, respectively (29). Unfortunately, few studies in this review included a direct measurement of muscle creatine uptake or dietary behaviors. Therefore it cannot be known if the difference or lack of a difference in muscle strength or weightlifting performance between the creatine- and placebo-supplemented groups resulted from the supplement, diet, exercise, or some other unknown factor.

Effect of Resistance Training Intervention

An interesting observation is the apparent lack of an effect of the design of the resistance training program used in these studies. That is, some studies were resistance training interventions (1–3, 5, 6, 12, 24, 33, 35, 36, 47–50, 52, 54, 55, 57), whereas other studies provided creatine or placebos to subjects who then followed an unsupervised training program of their own design (11, 26, 27, 46, 56). Also, in studies that used a training program consisting of either a single exercise (2) or training of a single body part (57), subjects ingesting creatine still experienced significantly greater increases in muscle strength. It is difficult to know why there were no apparent effects of the design of the resistance training intervention; it is possible that all of the training programs included in this review were alike enough to illicit a similar response.

Gender Differences

Forsberg et al. (13) previously reported higher baseline muscle creatine levels in women, but other researchers have reported similar baseline muscle creatine levels and no difference in muscle creatine uptake following creatine supplementation between genders (21). Higher baseline muscle creatine levels could blunt the increase in muscle creatine following creatine ingestion (15, 17, 21) and possibly reduce the response to the supplement in terms of muscle strength or weightlifting performance. One group has reported that men and women experience similar improvements in exercise performance following creatine supplementation (51), but that women show a lesser increase in lean body mass (32) and no reduction in protein breakdown (34) following creatine supplementation compared with men. Few data are available on the influence of gender on muscle creatine uptake.

Given similar increases in muscle creatine following creatine supplementation, it could be speculated that similar improvements in muscle strength and weightlifting performance following creatine supplementation plus resistance training could be expected between men and women. Although few studies focused on the combined effects of creatine supplementation and resistance training on muscle strength and weightlifting performance in women, it appears that the response is similar in magnitude to what is experienced by men. For instance, Vandenberghe et al. (54) reported greater improvements in 1RM in the leg press (creatine vs. placebo group, 43 vs. 25%); leg extension (85 vs. 57%); and squat (46 vs. 25%) in previously untrained women ingesting creatine during 10 weeks of resistance training. Brenner et al. (5) reported a 10% greater increase in the bench press in female athletes ingesting creatine during a 4.5-week resistance training program. Enette Larson-Meyer (12) found no difference in the response of female athletes ingesting creatine during 13 weeks of off-season resistance training compared with those ingesting a placebo, although the mean increase in 1RM was larger in the creatine group (bench press, 18 vs. 9%; squat, 24 vs. 12%). Thus, in consideration of the limited data available and the relatively small sample sizes studied, both men and women appear to benefit from creatine supplementation during resistance training.

Effect of Training Status

It is unlikely that resting muscle creatine is influenced by resistance training as no changes were reported in resting muscle creatine in the placebo groups following training (54, 55), but no studies have assessed the effects of training status on muscle creatine uptake or the magnitude of creatine uptake following creatine supplementation. It could be speculated that training might increase muscle creatine uptake because training is associated with improved insulin sensitivity, which may augment muscle creatine uptake (44). Thus a trained athlete could experience greater muscle creatine uptake than an untrained subject. The influence of training status on muscle creatine uptake is unknown, but the effect of training status on the combined effects of creatine supplementation and resistance training on muscle strength and weightlifting performance can be assessed from the data included in Table 1. Unfortunately, it is difficult to precisely assess the influence of training status because several studies simply categorized subjects as "resistance trained," rather than provide years of training experience. This makes it difficult to quantify the level of training experience of the subjects. However, when studies are separated into categories of trained and untrained, some observations can be made.

Of the studies included in this review, 18 studies examined trained subjects and 4 studies examined untrained subjects. The average increase in muscle strength following creatine supplementation plus resistance training was 14% in trained subjects and 31% in untrained subjects. This demonstrates 2 important points: (a) the combination of creatine plus resistance training is effective in increasing muscle strength in both trained and untrained subjects, and (b) it appears as if the combined effects of creatine supplementation plus resistance training are greater in untrained than trained subjects. A trained athlete who is closer to his or her maximal strength potential and makes smaller gains over a similar time period than an untrained individual, would have a smaller response to the treatment. This finding lends credibility to our analysis and interpretation of the studies included in this review. As previously mentioned, the average increase in weightlifting performance following creatine supplementation plus resistance training was 26%. Unfortunately, no studies assessed weightlifting performance following creatine ingestion during resistance training in untrained subjects, so we cannot speculate on the combined effects of creatine supplementation plus resistance training on weightlifting performance in this group.

Mechanism of Action

The increased muscle strength and improved weightlifting performance following creatine ingestion plus resistance training could result from several mechanisms, including greater gains in lean body mass (55); an effect on protein metabolism (34); an increase in myosin heavy chain mRNA and protein expression (57); an alteration in the expression of myogenic transcription factors (23); an increase in satellite cell mitotic activity (9); increased protein synthesis secondary to increased cellular swelling (3, 22); or simply an increase in the intensity of individual workouts resulting from a better match between ATP supply and demand during exercise (7). Of these variables, only the effects of training volume can be assessed from the current review.

We contend that the "beneficial" effects of creatine supplementation on muscle strength and weightlifting performance during resistance training are largely the result of the creatine-loaded subjects training at a higher workload than placebo-supplemented subjects. Since short-term creatine supplementation results in enhancement of both 1RM strength and weightlifting performance (55), part of the ergogenic effect of creatine shown in resistance training plus creatine intervention studies may be due to an acute effect of creatine and partly due to the ability of subjects to train at higher workloads. The relative contributions of these mechanisms remain unclear. Arciero et al. (1) compared 1RM strength gains after 4 weeks of creatine supplementation with or without resistance training. Bench press and leg press 1RM were increased 8 and 16%, respectively, in the creatine alone group and 18 and 42%, respectively, in the training group. This study suggests that approximately 40% of the increase in strength over the 4-week training and creatine supplementation period is due to the acute effects of creatine on force production, with the remaining 60% due to some other mechanism, presumably an ability to train with high workloads. An enhanced creatine/phosphocreatine energy system (i.e., increased muscle creatine and phosphocreatine stores following creatine ingestion) allows athletes to perform more repetitions per set of a given exercise (see Table 1) and may allow them to ''recover'' more rapidly between sets via accelerated phosphocreatine resynthesis (17). Additional support of this hypothesis are data from a previous study in which subjects ingesting creatine had increased bench press lifting volume during the resistance training intervention compared with subjects ingesting placebo (55). Further, Syrotuik et al. (49) reported that when training volume is equal, subjects ingesting creatine or placebo experience similar increases in muscle strength and weightlifting performance following an 8-week resistance training program. Thus it is probable that subjects who ingest creatine during resistance training do more work in the weight room than those who do not.

Summary

Creatine continues to be a popular nutritional supplement among athletes of a variety of ages and in many sports. However, athletes are not necessarily using creatine as a sports performance booster per se but instead are using creatine as a training aid during periods of intense resistance training. There is substantial evidence to indicate the creatine supplementation during resistance training is more effective at increasing muscle strength and weightlifting performance than resistance training alone. Although there is considerable variability in the increase in muscle strength and weightlifting performance in subjects ingesting creatine during resistance training, subjects ingesting creatine experience on average an 8% greater increase in muscle strength (20 vs. 12%) and a 14% greater increase in weightlifting performance (26 vs. 12%). Additionally, untrained subjects experienced a larger increase in muscle strength following creatine supplementation plus resistance training than trained subjects (31 vs. 14%). Although the unknown effects of chronic creatine ingestion remain largely unstudied, athletes will likely continue to ingest creatine for prolonged periods of time during periods of intense resistance training in the hopes that the ''benefits'' acquired in the weight room will translate into improved performance on the playing field.

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Acknowledgments

The authors wish to thank Priscilla Clarkson, Ph.D., for her thoughtful comments during the preparation of this manuscript.

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