# Effects of creatine supplementation on muscle power, endurance, and sprint performance

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## ABSTRACT

IZQUIERDO, M., J. IBAÑEZ, J. J. GONZÁLEZ-BADILLO, and E. M. GOROSTIAGA. Effects of creatine supplementation on muscle power, endurance, and sprint performance. *Med. Sci. Sports Exerc.*, Vol. 34, No. 2, pp. 332–343, 2002. **Purpose:** To determine the effects of creatine (Cr) supplementation (20 g·d$^{-1}$ during 5 d) on maximal strength, muscle power production during repetitive high-power-output exercise bouts (MRPB), repeated running sprints, and endurance in handball players. **Methods:** Nineteen trained male handball players were randomly assigned in a double-blind fashion to either creatine ($N = 9$) or placebo ($N = 10$) group. Before and after supplementation, subjects performed one-repetition maximum half-squat ($1RM_{HS}$) and bench press ($1RM_{BP}$), 2 sets of MRPB consisting of one set of 10 continuous repetitions (R10) followed by 1 set until exhaustion ($R_{max}$), with exactly 2-min rest periods between each set, during bench-press and half-squat protocols with a resistance equal to 60 and 70% of the subjects' 1RM, respectively. In addition, a countermovement jumping test (CMJ) interspersed before and after the MRPB half-squat exercise bouts and a repeated sprint running test and a maximal multistage discontinuous incremental running test (MDRT) were performed. **Results:** Cr supplementation significantly increased body mass (from $79.4 \pm 8$ to $80 \pm 8$ kg; $P < 0.05$), number of repetitions performed to fatigue, and total average power output values in the $R_{max}$ set of MRPB during bench press (21% and 17%, respectively) and half-squat (33% and 20%, respectively), the $1RM_{HS}$ (11%), as well as the CMJ values after the MRPB half-squat (5%), and the average running times during the first 5 m of the six repeated 15-m sprints (3%). No changes were observed in the strength, running velocity, or body mass measures in the placebo group during the experimental period. **Conclusion:** Short-term Cr supplementation leads to significant improvements in lower-body maximal strength, maximal repetitive upper- and lower-body high-power exercise bouts, and total repetitions performed to fatigue in the $R_{max}$ set of MRPB, as well as enhanced repeated sprint performance and attenuated decline in jumping ability after MRPB in highly trained handball players. Cr supplementation did not result in any improvement in upper-body maximal strength and in endurance running performance. **Key Words:** STRENGTH, MUSCLE POWER OUTPUT, ENDURANCE, CREATINE

During intense exercise of short duration, the adenosine triphosphate (ATP)-phosphocreatine (PCr) system is the predominant energy supplier for muscular work (15). When PCr becomes depleted, performance deteriorates because ATP cannot be resynthesized at the rate required (12,15,19,21). This has led to some authors to suggest that increasing resting levels of PCr availability after oral creatine (Cr) loading might delay PCr depletion and attenuate the decline in ATP provision during intense exercise or might accelerate the rate of PCr resynthesis after intense repeated exercise (12,19,21). It has been shown that oral Cr supplementation, in amounts substantially in excess of the normal dietary intake, can elevate the whole-muscle total Cr stores by approximately 20%, one third of which is in the form of PCr (12,14). Several studies have shown that short-term Cr supplementation may enhance the athlete's capacity to perform repeated muscular actions or bouts of high-intensity exercise and maintain power output as well as

delay onset of muscular fatigue, in addition to promoting faster recovery between bouts of intense exercise (4,8,11,21,38). However, other studies on creatine supplementation failed to show any potentially positive effects (10,25,30,36).

High-intensity resistance exercise may benefit from Cr loading because energy-rich phosphates significantly contribute to the energy yield during resistance tasks (23). Few studies have reported the short-term (<1 wk) effects of Cr supplementation on dynamic and constant resistance exercise (3). For instance, Volek et al. (37) showed that short-term Cr supplementation resulted in a significant improvement in the highest recorded peak power output achieved for a single repetition during all 5 sets of jump squats and a significant improvement in the number of repetitions during bench presses. To the authors' knowledge, no studies have reported the short-term (<1 wk) effects of Cr supplementation on the power output generated during maximal repetitive muscle contractions of the lower- and upper-extremity muscles in two resistance exercises with training loads typically undertaken by athletes (i.e., bench-press and half-squat exercises; 60–70% of 1RM). Therefore, one purpose of this study was to examine the effects of short-term Cr supplementation on maximal strength and muscular power

output during repeated sets of repetitive bouts of high-intensity power output of bench-press and half-squat exercise in highly trained handball players.

Moreover, the ability of creatine supplementation to improve performance and energy metabolism during weight-bearing activities as such repeated sprint runs (1,27,31,34) or during endurance exercise (4,27,33) remains controversial. Therefore, the second purpose of this study was to examine the effects of short-term Cr supplementation on repeated sprint runs and endurance performance in handball players. We choose handball players to investigate the effects of Cr loading on muscle power output, sprint performance, and endurance because during handball training and competition they perform frequent strenuous activities, such as repeated bouts of various sprints, throws, and jumping performances, interspersed with aerobic recovery periods (2). Accordingly, it was hypothesized that oral Cr supplementation could enhance performance during repeated sprints runs and during training-specific repetitive high-intensity power output exercise bouts, without having a detrimental effect on endurance running.

## METHODS

### Subjects

Nineteen experienced male handball players volunteered to participate in the study. All the subjects were members of the same team, played in the Spanish second division, and had a minimum continuous handball training background of $14.5 \pm 2$ yr of experience before the study. The subjects were trained by the same coach over the last 3 yr. This study was performed in February, during the competitive season (October to May), in the only week where no official game was played. During the 5 months before the beginning of the experimental period, the subjects trained four times a week for handball, once a week for strength and endurance training, and played in one official handball game per week. During the experimental period (in the only week where no official game was played), only the test procedures, as well as two practice handball sessions were carried out. The last strength-training session took place 5 d before the pretest. Practice handball sessions lasted 90 min and usually consisted of various skill activities at different intensities, offensive and defensive strategy, and 30 min of continuous play with only brief interruptions by the coach. The strength-training sessions were performed immediately before the handball training sessions. The strength-training program required each subject to perform a combination of free weights and exercise machines in each session, mainly consisting of 3 sets of 10–12 RM. The exercises completed in each weight-training session were the supine bench press, half-squat, and knee flexion curl. The total duration of each strength-training session was 35–40 min. The running endurance program consisted of one training session per week and lasted 20–30 min at a self-adjusted intensity. Only subjects that had never been supplemented with creatine monohydrate/maltodextrin or had never used anabolic steroids or beta-agonists were eligible for participation to avoid unknown subsequent physiological adaptations; the subjects were aware of their supplementation condition. After baseline testing, subjects were matched according to physical characteristics, muscle strength/power, velocity, and endurance indices and then randomly assigned in a double-blind fashion into a creatine ($N = 9$) and placebo ($N = 10$) group. They were informed carefully on the experimental procedures and about the possible risks and benefits of the project design. The experimental procedures were approved by the Institutional Review Committee of the Instituto Navarro de Deporte y Juventud, according to the declaration of Helsinki. Each subject signed a written informed consent form before participation in the study.

### Experimental Design

This study utilized a two-group matched, doubled-blind, randomly assigned design. Subjects completed a 2-d experimental protocol on two different occasions separated by 7 d, before the 5-d supplementation period and at the end. Body weight and body fat estimates from the measurements of seven skin-fold thickness (17) were taken at the beginning of both testing sessions. During the first testing session, each subject was tested for his one concentric repetition maximum (1RM) from a bench-press ($1RM_{BP}$) and half-squat ($1RM_{HS}$) position. After 1RM testing, the subjects performed maximal repetitive high-power-output exercise bouts with submaximal loads during a bench-press and half-squat protocol. The countermovement jumping test was interspersed before and 3–7 s after the maximal repetitive high-power-output half-squat exercise bouts. In the second test session, each subject performed a repeated sprint running test (RPRT) followed by 10 min of rest for a maximal multistage discontinuous incremental running test (MDRT). For a given subject, muscle strength and endurance tests took place at the same time of day throughout the experiment. All the subjects were familiarized with the testing protocol, as they had been previously tested on several occasions during the season with the same testing procedures. The test-retest intraclass correlations coefficients of the testing procedure variables used in this study were greater than 0.91, and the coefficients of variation (CV) ranged from 0.9% to 7.3% (unpublished results).

### Performance Testing

**Maximal strength and muscle power output.** During the first test session, lower- and upper-body maximal strength was assessed using one-repetition concentric maximum bench-press ($1RM_{BP}$) and half-squat ($1RM_{HS}$) actions. In $1RM_{BP}$ protocol the bar was positioned 1 cm above the subject's chest and supported by the bottom stops of the measurement device. The subject was instructed to perform, from the starting position, a purely concentric action maintaining the shoulders in a 90° abducted position to ensure consistency of the shoulder and elbow joints throughout the testing movement. No bouncing or arching of the back was allowed. In $1RM_{HS}$ protocol the shoulders were in contact

with a bar and the starting knee angle was 90°. On command, the subject performed a concentric leg extension (as fast as possible) starting from the flexed position to reach the full extension of 180° against the resistance determined by the weight plates added to both ends of the bar. The motion was completed when the torso was upright. All the tests were performed in a squatting apparatus in which the barbell was attached to both ends, with linear bearings on two vertical bars allowing only vertical movements. Warm-up consisted of a set of 5 repetitions at the loads of 40–60% of the perceived maximum. Thereafter, four to five separate single attempts were performed until the subject was unable to extend the legs or arms to reach the full extension. The rest between maximal attempts was always 2 min.

**Maximal repetitive high-power-output exercise bouts with submaximal loads.** After 5-min rest, the subjects performed a maximal-repetitive high-power-output exercise bouts with submaximal loads during half-squat and bench-press protocols. The bench-press protocol consisted of one set of 10 continuous repetitions (R10) with a resistance equal to 60% of the subject's $1RM_{BP}$, followed by one set until fatigue ($R_{max}$), with exactly 2-min rest periods between each set. The half-squat protocol consisted of one set of 10 continuous repetitions with a resistance equal to 70% of the subjects' $1RM_{HS}$, followed by one set until fatigue with the same load, with exactly 2-min rest periods between each set. The subjects were asked to move the bar as fast as possible during the concentric and eccentric phase of each repetition, until they were unable to reach the full extension position of the arms or legs. Fatigue was defined at the time point when the bar ceased to move, if the subject paused more than 1 s when the legs or arms were in the extended or flexed position, or if the subject was unable to reach the full extension position of the arms or legs. The cadence of each repetition was controlled with a metronome with a frequency of 19 Hz.

During the upper- and lower-extremity test actions, bar displacement, average velocity ($m \cdot s^{-1}$), and mean power (W) were recorded by linking a rotary encoder to the end part of the bar. The rotary encoder recorded the position and direction of the bar within an accuracy of 0.2 mm and time events with an accuracy of 1 $\mu s$. Customized software (JLML I+D, Madrid, Spain) was used to calculate the power output for each repetition of half-squat and bench-press performances throughout the whole range of motion used to perform a complete repetition.). The velocity (v; $m \cdot s^{-1}$) was calculated each instantaneous displacement ($\Delta d$) of 0.2 mm by using the following equation:

$$V = \Delta d \cdot \Delta t^{-1},$$

where $\Delta t$ is the time (s) to perform the instantaneous range of displacement (0.2 mm) with a resolution of 1 $\mu s$. The calculation of instantaneous power was then calculated by multiplying the velocity over each displacement period by force derived from the product of mass of the load and acceleration due to gravity. Average power for each repetition was calculated as the means of all instantaneous power values measured during all the time necessary to perform a complete repetition. Total repetitions for each set of bench presses and average power output for each repetition of half-squat and bench press were determined. The average power value obtained for each repetition was used to calculate the total average power generated during each set of exercise in both groups. Power curves were plotted using average power over the whole range of movement as the most representative mechanical parameter associated with a contraction cycle of each muscle group.

**Jumping test.** Before 1RM half-squat assessment and after completion of each set of the half-squat protocol, subjects were instructed to walk to the contact platform (Newtest Oy, Oulu, Finland) situated close to the barbell and immediately perform two maximal countermovement jumps (CMJ). The time delay between finishing the half-squat protocol and performing the first jump was between 3 and 7 s. The second jump was always performed 4 s after the end of the first jump. The subjects were asked to perform a CMJ on the contact platform with a preparatory movement from the extended leg position down to the 90° knee flexion, followed by a subsequent concentric action. The jumping height was calculated from the flight time. Two maximal jumps were recorded interspersed with approximately 10 s of rest and the peak value was used for further analysis.

**Repeated sprint runs.** The repeated sprint runs (RPRT) and the endurance running tests were performed in the second test session, at the same time of day, and in the same indoor handball court. After a standardized 15-min warm-up period that included low-intensity running, several acceleration runs, and stretching exercises, the subjects undertook a sprint running test consisting of six maximal sprints of 15 m, with a 60-s rest period between each sprint. Stance for the start was consistent for each subject. During the 60-s recovery period, the subjects walked back to the starting line. The recording of running time was done by using photocell gates (Newtest Oy), placed 0.4 m above the ground and placed at 0.5 m, 5.5 m, and 15.5 m.

**Endurance running test.** Ten minutes after the end of the RPRT test, the subjects performed a maximal discontinuous incremental running test (MDRT) around the handball court (40 × 20 m) until volitional exhaustion. The initial velocity was 10 $km \cdot h^{-1}$ and then was increased in a step-wise fashion by 2 $km \cdot h^{-1}$ every 5 min, until volitional exhaustion or the required running velocity could not be maintained. After each stage, the test was interrupted for 3 min before initiating the next stage. To assure a constant velocity for each running stage, the subjects were instructed to pace their running through an audio signal connected to a preprogrammed computer (Balise Temporelle, Bauman, Switzerland). During the test, heart rate was recorded every 15 s (Polar Vantage NV, Polar Electro, Kempele, Finland) and averaged for the last 60 s of each stage. Immediately after each exercise stage, capillary blood samples for the determination of lactate concentrations were obtained from a hyperemic earlobe. Samples for the whole blood lactate determination (100 $\mu L$) were deproteinized, placed in a preservative tube (YSI 2315 Blood Lactate Preservative Kit, Yellow Springs, OH), stored at 4°C, and analyzed (YSI

1500) within 5 d after completing the test. According to the manufacturer's instructions, placing the capillary samples in these preservative tubes allows the blood samples to be stored for 3–5 d with stable blood lactate concentration values (pooled estimate of standard deviation: 0.15 $mmol \cdot L^{-1}$ for a concentration range of 0–10 $mmol \cdot L^{-1}$). The blood lactate analyzer was calibrated after every fifth blood sample dosage with three known controls (5, 15, and 30 $mmol \cdot L^{-1}$).

## Urinary Creatinine

Twelve-hour overnight urine samples were collected in containers the day before and the morning after 5 d of treatment. After collection, all samples were measured for urinary volume, and mixed samples were immediately analyzed for urinary creatinine concentration by spectrophotometry using a Synchron CX7 apparatus (Beckman Instruments Inc., La Brea, CA).

## Supplementation Procedure

After baseline testing, subjects were asked to consume either 5 g of creatine monohydrate (Cr, $N = 9$) or an equivalent volume of maltodextrin (placebo, $N = 10$), four times daily for the next 5 d. Each supplement was measured using electronically calibrated scales and placed in identical coded airtight bags. The subjects mixed the supplement powder in approximately 0.25 L of warm-to-hot water for better dissolution of creatine (14) and ingested the solution with morning, mid-day, afternoon, and evening meals. Cr and placebo were administered in a double-blind fashion. The supplementation was initiated right after the baseline testing and ended the same day of the first performance testing postsupplementation session. This dosage pattern of creatine administration was chosen because it has been shown to produce significant increases in resting muscle PCr levels in men (14). Compliance with the supplement was 100%. We also assessed creatinine urinary levels to support this approach. When asked verbally at the end of the study, the subjects did not know the supplementation they had received.

## Statistical Methods

Standard statistical methods were used for the calculation of the means and standard deviations. A $t$-test for unpaired samples indicated that there were no baseline differences among the two groups' initial maximal strength, repetitive high-power-output exercise bouts, number of repetitions during a half-squat and bench press, and endurance and sprint running measures. Corresponding pre- and post-supplementation values for all measured variables were compared via a two-way analysis of variance (ANOVA, group × time) with repeated measures design. When a significant $F$-value was achieved, Scheffé *post hoc* procedures were performed to locate the pairwise differences between the means. The $P \leq 0.05$ criterion was used for establishing statistical significance.

# RESULTS

## Body Mass

The physical characteristics of the creatine and placebo groups were (mean ± SD): age, 20.8 ± 5 and 23.6 ± 5 yr; height, 182 ± 8 and 189.7 ± 8 cm; body mass 79.4 ± 8 and 87 ± 12 kg; percent body fat, 10.7 ± 3 and 11.3 ± 3%, respectively. No significant differences between the two groups were noted in age, height, body mass, and percent body fat at presupplementation measurement. There was significant group × time interaction, with significantly greater ($P < 0.01$) increases in body mass after supplementation in Cr group than in the placebo group. In the Cr subjects, body mass increased significantly ($P < 0.05$) from 79.4 ± 8 to 80 ± 8 kg, during the supplementation period. No significant changes were observed in the body mass of the placebo subjects throughout the experimental period (87 ± 12 and 86.8 ± 11 kg, before and after the supplementation period, respectively). No significant change in percent body fat was observed in the creatine (10.7 ± 3 and 10.3 ± 3%) and placebo groups (11.3 ± 3 and 10.9 ± 3%, before and after the supplementation period, respectively).

## Maximal Strength

Maximal $1RM_{BP}$ and $1RM_{HS}$ values are shown in Figure 1. Neither group showed significant changes in the maximal $1RM_{BP}$ after the supplementation period. There was significant group × time interaction, with significantly greater ($P < 0.01$) increases in $1RM_{HS}$ in Cr group than in the placebo group. In Cr subjects, $1RM_{HS}$ increased significantly from 133 ± 11.9 to 147.7 ± 14.1 kg ($P < 0.001$) during the supplementation period. In contrast, no significant changes were observed in the $1RM_{HS}$ of the placebo subjects throughout the experimental period.

**Maximal repetitive high-power-output exercise bouts with submaximal loads.** The data for average power produced pre- and post-supplementation produced during each repetition of bench press (60% of $1RM_{BP}$) during the R10 and $R_{max}$ sets are presented in Figure 2. After the initial maximum, average power production in the bench-press action declined consistently and followed the same pattern in both groups during the R10 set (Fig. 2, A and B). In both groups, there were no differences in the individual average power for each repetition and in the total average power values during the R10 set of the bench-press action, before and after the supplementation period. A significant group × time interaction was found in the $R_{max}$ set, with a significantly greater ($P < 0.05$–0.01) mean improvement in the number of repetitions and total average power production values of repetitions performed to fatigue after Cr supplementation compared with the placebo group. During the second set ($R_{max}$) of the bench press, no significant changes were observed for the placebo group before and after the supplementation period in average muscle power output in each repetition, in the total average power output values of repetitions performed to fatigue (240 ± 35,2 vs 236 ± 42 W), and in the number of repetitions to fatigue
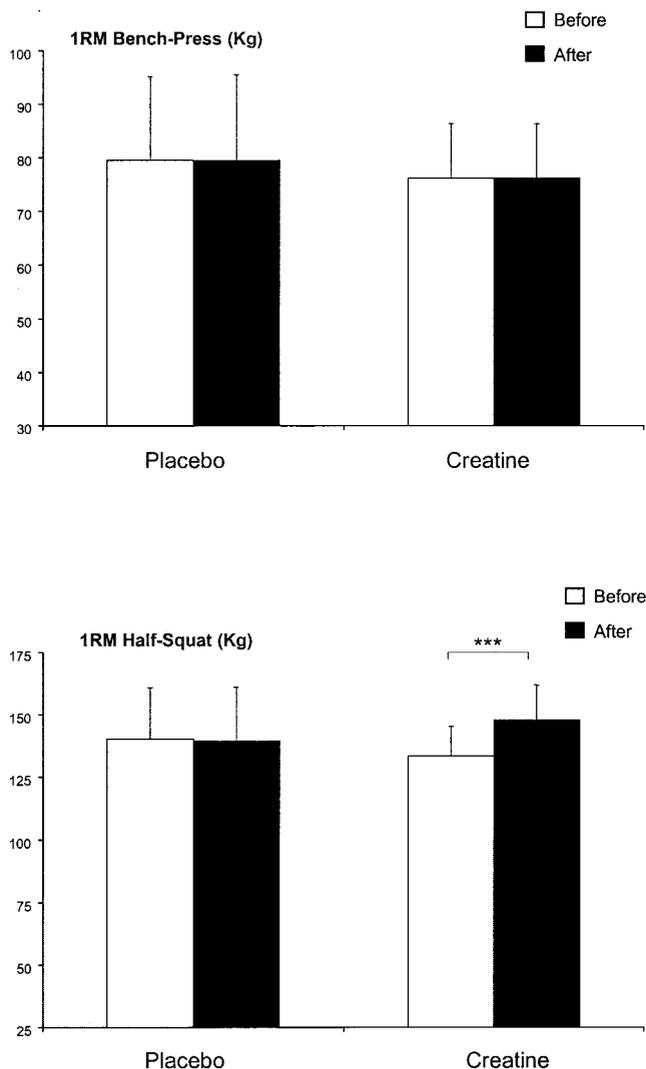
**FIGURE 1—One-repetition maximum (1RM) bench press and half-squat before and after the creatine or placebo supplementation period. *** Denotes a significant difference between pre-and post-supplementation ($P < 0.001$). Values are means ± SD. Significant pre-/post-supplementation differences were tested after a significant (group × time) interaction was found. See text for details.**

($15.7 \pm 3.8$ vs $16.8 \pm 4.9$, pre- and post-supplementation, respectively) (Fig. 2C). Creatine supplementation consistently increased posttreatment total average muscle power output performed to fatigue ($248 \pm 49$ vs $262 \pm 63$ W; $P < 0.05$, pre- and post-supplementation, respectively) and the number of repetitions to fatigue ($16.1 \pm 2.9$ vs $18.8 \pm 3.5$; $P < 0.05$, before and after supplementation, respectively) in $R_{max}$ set of the bench press.

The data for the average power produced pre- and post-supplementation during each repetition in the half-squat action (70% of $1RM_{HS}$) during the R10 and $R_{max}$ sets are presented in Figure 3. In both groups, there were no differences in the individual average power produced for each repetition during R10 and $R_{max}$ sets of the half-squat action, before and after supplementation. There was a significant group × time interaction for the total average power production values of repetitions performed in the R10 set of the half-squat performance; the mean improvement in total av-

erage power production values in Cr group was significantly greater ($P < 0.01$) after supplementation than in the placebo subjects. In the placebo group, there were no significant differences in the total average power produced values performed in R10 set of the half-squat, before and after supplementation (Fig. 3A). However, after 5 d of Cr ingestion, the total average power produced values ($557 \pm 107$ vs $605 \pm 123$ W, $P < 0.01$) performed in R10 set of the half-squat were significantly greater than before supplementation (Fig. 3B).

A significant group × time interaction was observed for the number of repetitions and total average power production values of repetitions performed to fatigue in the half-squat action. For the Cr group, the mean improvement in the number of repetitions and total average power production values of repetitions performed to fatigue was significantly greater ($P < 0.01$) after supplementation than in the placebo subjects. During the $R_{max}$ set of the half-squat, no significant changes were observed before and after the supplementation period for the placebo group, in average muscle power output in each repetition, the total average power output values of repetitions performed to fatigue ($514 \pm 107$ vs $520 \pm 108$ W, pre- and post-supplementation), and in the number of repetitions to fatigue performed with the 70% of $1RM_{HS}$ ($13.8 \pm 5$ vs $13.5 \pm 4.4$ pre- and post-supplementation, respectively) (Fig. 3C). Creatine supplementation consistently increased posttreatment total average power output values of repetitions performed to fatigue ($514 \pm 99$ W vs $566 \pm 118$ W; $P < 0.001$, pre- and post-supplementation respectively) and the number of repetitions to fatigue ($13.2 \pm 3.0$ vs $15.9 \pm 2.1$; $P < 0.01$, before and after supplementation, respectively) in $R_{max}$ set of the half-squat (Fig. 3D).

**Countermovement jump (CMJ).** Figure 4 shows the countermovement vertical jump values (CMJ) at rest, at the end of R10 set of the half-squat (PostR10), and at the end of $R_{max}$ set of the half-squat (Post$R_{max}$), in the placebo group (Fig. 4A) and in the Cr group (Fig. 4B). Significant group × time interaction was observed for the CMJ at post R10 ($P < 0.01$). Thus, for the Cr group, the mean change in the CMJ values at PostR10 decreased to a lesser extent ($P < 0.05$) after supplementation compared with the placebo subjects. At the end of the first (PostR10) and the second (Post$R_{max}$) set repetitions of the half-squat, a significant decline in CMJ values was observed in both groups. However, an attenuated decline in jumping ability was observed in the Cr group after the first set of 10 repetitions. Thus, the CMJ values at the end of the first set of 10 repetitions of the half-squat were enhanced after Cr supplementation (from $31.4 \pm 1$ to $33.1 \pm 1$ cm; $P < 0.05$, pre- and post-supplementation, respectively), whereas the placebo group's jumping height remained unchanged ($30.1 \pm 1$ vs $30.3 \pm 1$ cm, pre- and post-supplementation, respectively). In the placebo and Cr subjects, there were no significant changes in the jumping height reached after the completion of the set of maximum repetitions to fatigue (Post$R_{max}$) in a half-squat action.
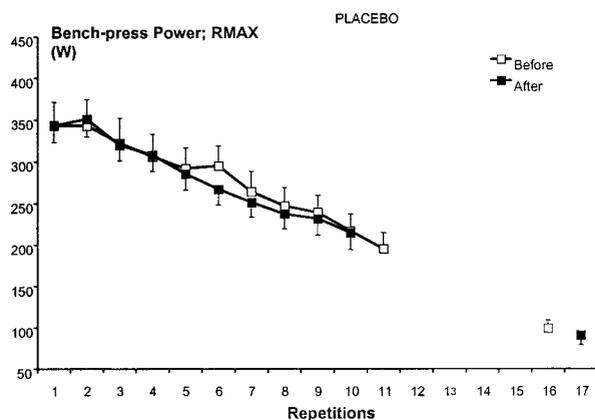
**Repeated sprint runs.** The run time remained constant during the repeated maximal-effort 15-m sprints. Creatine supplementation did not improve average running
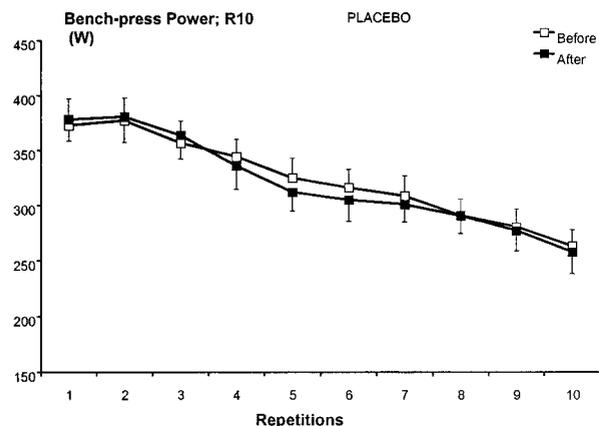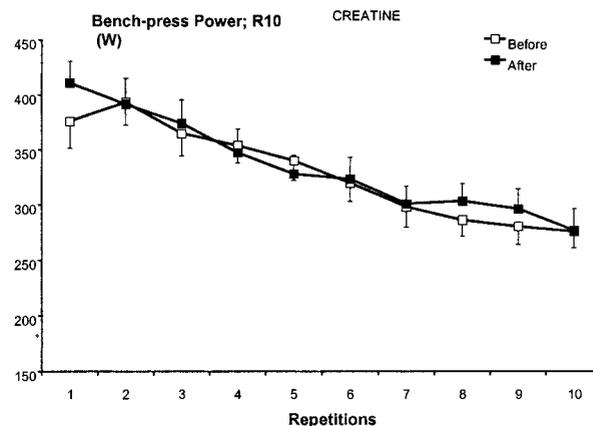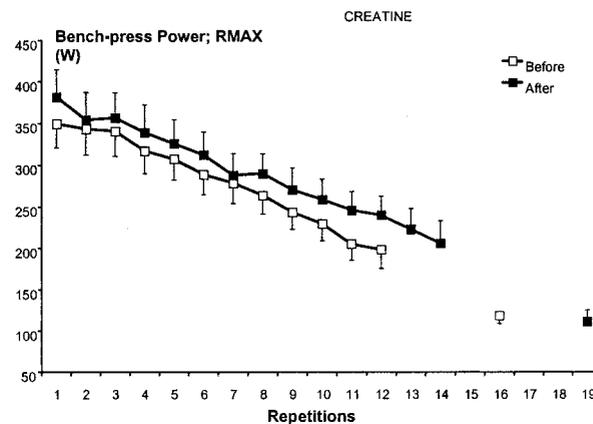
**FIGURE 2**—Average muscle power pre- and post-supplementation for each repetition during a bench-press exercise during a set of 10 repetitions (R10; A and B), followed after a 2-min rest by a set of maximum repetitions to fatigue ($R_{max}$; C and D) with the 60% of 1RM bench press. Values are means ± SD. The data points correspond to the average power output for each repetition of bench press during an R10 set (A and B) and to the average power output for each repetition that were completed by all subjects during an $R_{max}$ set (C and D). The stand-alone points in panels C and D correspond to the average power output for the last repetition performed for each subject in an $R_{max}$ set.

times for 15-m repeated sprints but did improve running time on the first 5 m of the 15-m repeated sprints (Fig. 5). There was a significant group × time interaction, with a significantly greater ($P < 0.05$) mean improvement in the average running time for 5-m distance after Cr supplementation compared with the placebo group. Average running times for 5-m distance of the six repeated sprints also improved significantly ($P < 0.05$) in the Cr group from 1.05 ± 0.03 to 1.03 ± 0.03 s pre- and post-supplementation, respectively. In the placebo group, no significant improvement was observed at the 5- and 15-m sprint running times throughout the experimental period.

**Maximal incremental endurance running test.** The values of the average blood lactate concentration–running velocity curves differed between the groups (Fig. 6). A significant decrease in mean blood lactate concentration was observed in the placebo group at running velocities of 10 km·h$^{-1}$ (from 2.2 ± 1.1 to 1.8 ± 1 mmol·L$^{-1}$, $P < 0.05$) and 12 km·h$^{-1}$ (from 3.1 ± 1.6 to 2.7 ± 1.6 mmol·L$^{-1}$, $P < 0.01$), before and after supplementation, respectively (Fig. 6A). No significant changes were observed in mean blood lactate concentrations in the Cr group at these velocities

(Fig. 6B). In the placebo group, mean decreases in blood lactate at running velocities of 12 km·h$^{-1}$ were significantly greater ($P < 0.05$) than in the Cr group. Average time to exhaustion attained during the MDRT was unchanged in the placebo group (1181 ± 158 vs 1166 ± 161 s) and in the creatine group (1163 ± 125 vs 1152 ± 133 s). The maximal values of blood lactate concentration and heart rate remained unaltered throughout the study in both groups. No significant differences were observed in time to exhaustion between groups.

**Urinary Creatinine**

There was a significant group × time interaction, with significantly greater ($P < 0.05$) average increases in urinary creatinine in the Cr group compared with the placebo group, urinary creatinine excretion increased significantly in the creatine group (141 ± 53, vs 248.9 ± 76.1 mg·dL$^{-1}$; $P < 0.001$), whereas it remained unchanged in the placebo group (155.7 ± 67.7 vs 157.6 ± 58.9 mg·dL$^{-1}$) after 5 d of supplementation. Urinary volume remained unaltered after 5 d of supplementation in either the placebo (45.6 ± 25.2 vs
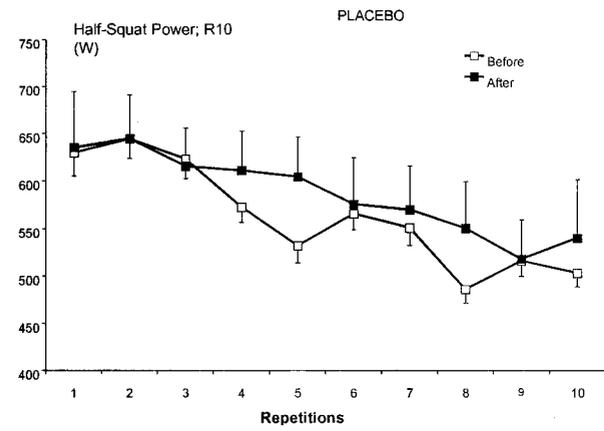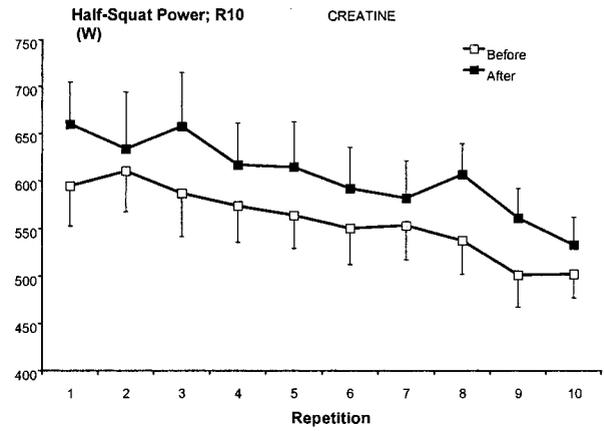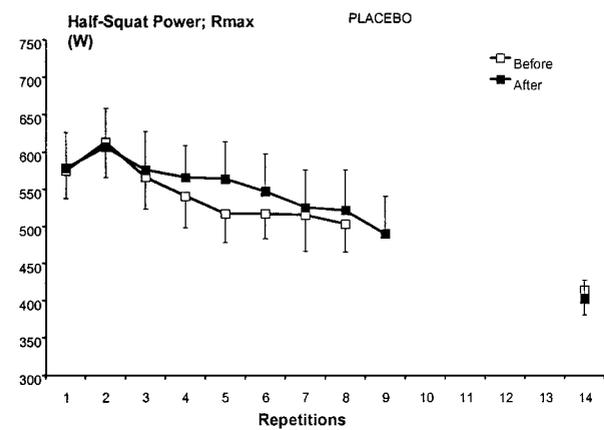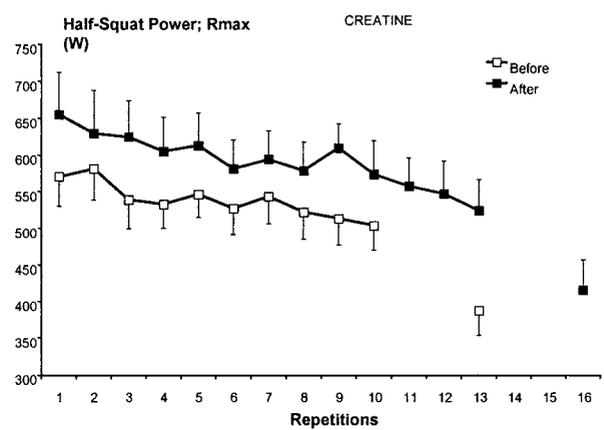
FIGURE 3—Average muscle power pre- and post-supplementation in each repetition during a half-squat press exercise during a set of 10 repetitions (R10; A and B), followed after a 2-min rest by a set of maximum repetitions to fatigue ($R_{max}$; C and D) with the 70% of 1RM half-squat. Values are means ± SD. Data points are as described in Figure 2.

$56.7 \pm 20$ mL·h$^{-1}$) and the creatine subjects ($50.2 \pm 15$ vs $41.6 \pm 15$ mL·h$^{-1}$) pre- and post-supplementation, respectively.

## Side Effects

No reports of gastrointestinal distress and/or medical problems/symptoms were observed during the supplementation period. There was no evidence of muscular cramping or muscle injury during handball training and games or during testing trials.

## DISCUSSION

The present study demonstrated that short-term Cr supplementation (20 g·d$^{-1}$ for 5 d) led to significant improvements in lower-body maximal strength, maximal repetitive upper- and lower-body high-power exercise bouts, and total repetitions performed to fatigue during sets of bench-press and half-squat actions in highly trained handball players. The enhancement was more marked in the lower- than in the upper-extremity muscles. Creatine-supplemented handball players showed improved performance during the first 5 m

of repeated bouts of 15-m sprint runs, as well as an attenuated decline in jumping ability after submaximal repetitive high-power-output half-squat exercise bout. Furthermore, the present results show that Cr supplementation did not result in any improvement in upper-body maximal strength and in endurance running exercise.

A significant improvement after short-term Cr supplementation has been previously reported in the number of repetitions completed during multiple sets of isotonic bench-press (37) and isokinetic, concentric-only, knee-extension contractions (11). The present study demonstrated that in trained subjects Cr supplementation significantly enhanced maximal repetitive power production during sets of bench-press and half-squat resistance exercises. This confirms the finding of Volek et al. (37) with jump squats and Greenhaff et al. (11) with isokinetic knee-extension contractions that short-term Cr supplementation may improve muscle power output during repetitive bouts of resistance exercise (39). Although muscle creatine concentration was not measured in the present study, the increased ability of the Cr group to perform a greater total lifting volume and generate more total average muscle power suggests that

**Height in CMJ (cm)** — PLACEBO

(A)



**Height in CMJ (cm)** — CREATINE
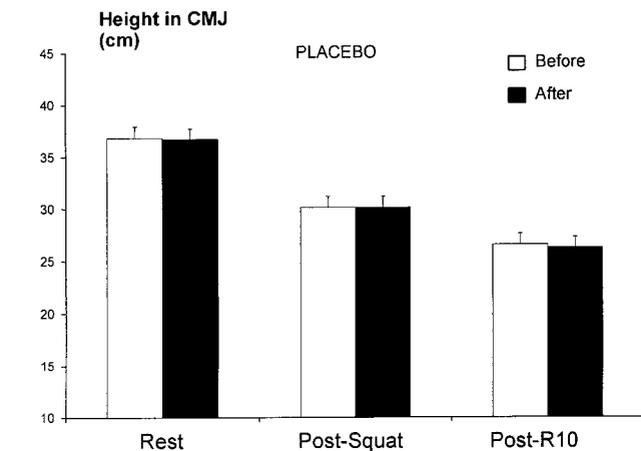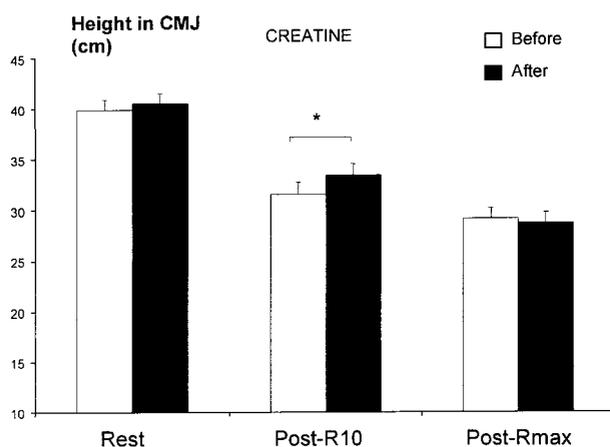
(B)

**FIGURE 4—Countermovement vertical jump values (CMJ) at rest, at the end of the first set of 10 repetitions of the half-squat (PostR10), and at the end of the second set (repetitions to fatigue) of the half-squat (PostR$_{max}$) in the placebo group (A) and in the creatine group (B), pre- and post-supplementation. \* Denotes a significant difference between pre- and post-supplementation ($P < 0.05$) Values are means ± SD. Significance are as described in Figure 1.**

creatine loading appears to enhance muscular performance during intermittent resistance exercise. This increased capacity to perform more repetitions and generate more power output may reflect increases in intramuscular PCr stores (14), increased ATP provision and attenuated reduction in ATP with repeated work tasks (11,13,20), a reduction of muscle adenine nucleotide loss (11), an increased velocity of PCr resynthesis during recovery periods after muscle contractions (11,13,20), and an increased potential for PCr to work as an ion H+ buffer (18). It is also likely that this ability to perform greater muscle power during a resistance-training session after Cr supplementation may allow athletes to complete their workouts at a higher intensity (3,38) and increase their adaptive responses in muscular structure and function (8).

After 5 d of Cr supplementation, a significant acute increase (11%) was observed in 1RM half-squat, whereas it remained unaltered in the placebo group. An explanation of this unexpected finding is difficult to interpret because increases in maximal muscular strength (1RM) are generally not thought to be limited by phosphagen metabolism (38). However, taking into account the total duration of the muscular contraction during a 1 RM half-squat, an extremely rapid degradation of PCr should be expected to occur during this type of exercise. Thus, in the present study, the average measured duration of the dynamic phase during the 1 RM half-squat test was 1.56 s. Assuming a previous isometric phase duration of 0.5–1 s, this would mean a total muscular contraction time of 2.0–2.5 s during a 1 RM half-squat test. Greenhaff et al. (13) estimated that the peak rates of ATP production from PCr begins to decline after only 1.3 s of contraction during isometric and dynamic maximal muscular actions in humans. After this peak, there is a progressive decline in ATP provision and a parallel decline in force production and power output (13). This means that during a 1 RM half-squat, PCr contributes a large fraction of the total ATP supply and there is an extremely rapid rates of ATP production and PCr degradation. It may be suggested that raising the total Cr concentration after Cr supplementation will not only increase the amount of PCr initially available for contraction but might also retard the moment when the peak rates of ATP production from PCr begin to decline. This delay might substantially enhance the rate of ATP synthesis and the amount of power generated during the few first seconds of duration of a very power-demanding exercise as such 1 RM. Therefore, an improved power-generating capacity during the few first seconds of exercise after short-term Cr loading could explain the increase in 1RM half-squat exercise. Another plausible explanation for this initial improvement in 1RM half-squat could be the decreased intensity and duration of the handball and strength/endurance training sessions that took place during the week of the study. Finally, the protocol for determination of 1RM dynamic strength could have some influence on the observed enhancement of 1 RM after Cr supplementation (3,19). Thus, 1 RM dynamic strength is determined by 3–6 progressive contraction efforts to establish the maximum separated by only 2-min rest. It is likely that the increased rate of PCr replenishment (between efforts) found during recovery after Cr supplementation (13) would allow for higher muscle strength levels during the subsequent bout of exercise, translating into improved 1 RM half-squat (3,38).

Cr supplementation differentially affected improvements in upper- and lower-extremity strength because 1RM bench press remained unaltered in both the placebo and creatine group, whereas creatine induced enhancement in 1RM half-squat. In addition, Cr supplementation significantly improved the average power output during both sets of half-squat but only improved the average power output during the second set of bench-press exercises. Differences in maximal strength and repeated bouts of submaximal muscle contractions between upper- and lower-extremity muscles have been already observed after short-term Cr loading in isometric-type contractions (35). The greater ability of Cr to enhance measures of strength and power in activities
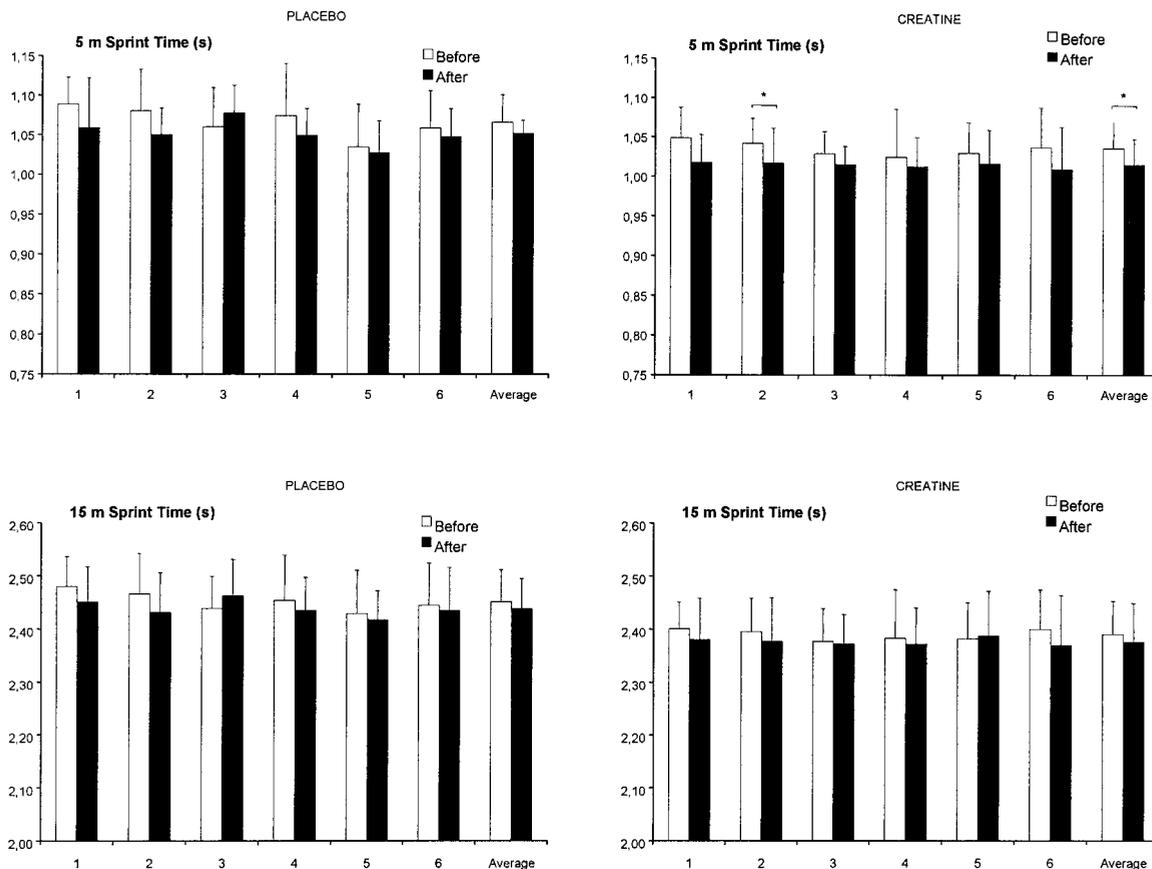
**FIGURE 5—Five- and 15-m run times during the repeated sprint test before and after the creatine or placebo supplementations period. * Denotes a significant difference between pre- and post-supplementation ($P < 0.05$). Values are means ± SD. Significance are as described in Figure 1.**

involving larger muscle groups might be explained by differences in the pattern of quantity and/or intensity of daily physical use in normal life and handball training. The quadriceps muscle, owing to its weight-bearing role during habitual activity and handball training, would more likely be exercised than the upper-body muscles, which are used less frequently. It has been shown that exercise may provide an additive effect relative to muscle Cr uptake during Cr supplementation (14), probably related to a higher uptake of Cr in exercised muscles. Therefore, the greater gains in strength and power made by the legs after Cr supplementation might be partly related to an enhanced Cr loading in the leg muscles due to a higher degree of solicitation during daily physical activity and handball training. Nevertheless, the potential role of creatine supplementation and phosphagen metabolism in mediating acute increases in maximal strength of upper- and lower-extremity muscle performance needs further attention.

Although Cr supplementation induced an increase in body mass, single vertical jump performance at resting condition was not impaired in the Cr group. These results agree with other studies performed with male subjects (27) and suggest that short-term Cr loading does not appear to significantly affect a single high-intensity explosive performance, which seems to be rather limited by the intrinsic limitations of the contractile proteins (i.e., rate of calcium acto-myosin ATPase activity) or by motor unit recruitment

(28). However, the Cr group was able to maintain a significant higher postsupplementation jumping performance level after completion of the first set of 10 repetitions with the 70% of 1 RM half-squat, whereas the placebo group did not show any significant change after the intervention period. A similar finding has been reported by Mujika and coworkers (27), who observed an attenuated decline in jumping performance after a maximal intermittent soccer-specific test (40 × 15-s bouts of high-intensity running interspersed by 10-s bouts of low-intensity running) after 5 d of creatine loading (20 g·d$^{-1}$). Greenhaff et al. (11) found that after Cr supplementation there is an increased velocity of PCr resynthesis during recovery from intense muscle contraction. Bogdanis et al. (7) found that the resynthesis of muscle PCr and the restoration of peak power output proceeded in parallel after a 30-s cycle sprint. Taking these observations together, it can be suggested that the attenuated decline in jumping ability observed after the first set of 10 repetitions with the 70% of 1RM half-squat in the Cr group could be related to a facilitated generation of intramuscular PCr occurring during recovery, probably as a consequence of an increase in Cr availability.

Creatine supplementation significantly improved performance during the first 5 meters of repeated bouts of 15-m sprint runs. These results confirm previous findings observed in our laboratory with highly trained soccer players (27) and others with handball players (1) and suggest that Cr
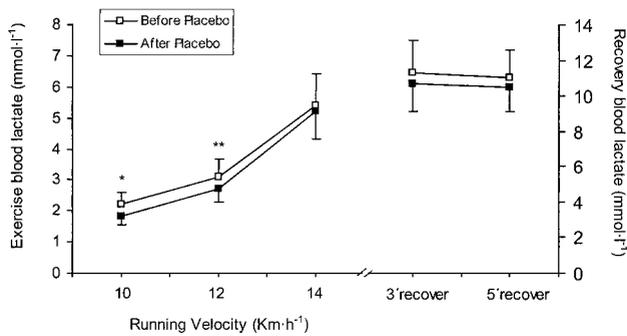
(A)
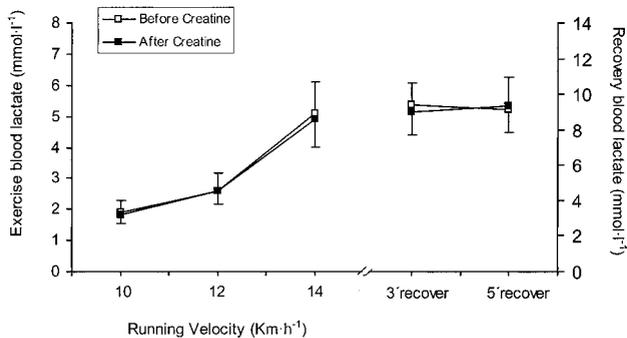


(B)

**FIGURE 6—Blood lactate concentrations during a maximal discontinuous incremental running test in absolute values before and after the creatine or placebo supplementation period (*$P < 0.05$; **$P < 0.01$ between pre- and post-supplementation). Values are means ± SD. Significance are as described in Figure 1.**

supplementation provides a potential benefit in energy provision during very short-term, high-intensity exercise, especially when performed in repeated succession. However, these results differ from other studies in which no ergogenic effects (22,31,32) or mixed effects (29,34) were found on sprint running performance after Cr supplementation. The conflicting results between studies regarding the effects of Cr supplementation on sprint running performance could be attributed to differences in the amount of repetitions and frames or distances tested. Indeed, the studies that have found no effects or mixed effects of acute Cr loading tested sprint running performance with only a single bout (22,29,34) or with repeated bouts of distances greater than 15 m (31,32). As mentioned previously, a clearer improvement in sprint performance after Cr loading should be expected during repeated short supramaximal exercise of 1- to 2-s duration because: 1) during this time frame, PCr generates the highest peak rates of ATP production (13); 2) PCr availability is critical for power generation during the initial seconds of exercise (6); and 3) Cr loading may increase the rate of PCr resynthesis during recovery periods after muscle contractions (11,13). When only one bout of sprint running is performed and/or the time frame of each bout is higher than 1–2 s, the effects of Cr loading should be less pronounced and could be hindered by the absence of effect of PCr resynthesis during recovery periods (single bout), a

lower contribution of PCr to ATP provision and the increase in body mass that normally occurs with Cr loading. From a practical point of view, it may be interesting to point out that the improvement in repeated sprint runs and in body mass found in the present study after Cr supplementation may be advantageous for very high contact sports, such as handball.

Most of the studies focused on endurance exercise do not support the ergogenic effect of acute Cr supplementation or even may argue an ergolytic effect on it (4,9,27,33), partly due to creatine-induced increases in body mass with consequently higher absolute rate of $O_2$ consumption, as well as to the expected smallness role that the PCr system plays in muscle function during exercise of this nature (3,4,9,27,33). The theoretical mechanism for supporting the possible ergogenic effects of Cr supplementation on submaximal exercise performance relies on the role of cytosolic Cr as an acceptor of mitochondrial ATP (6,26). In the present study, during the maximal multistage discontinuous incremental running test, lower blood lactate concentrations were observed in the placebo group at 10 $km·h^{-1}$ and 12 $km·h^{-1}$ after the administration period, whereas no changes were observed in the Cr group. It has been suggested that a decrease in blood lactate concentrations during submaximal exercise as a result of training is associated with improved endurance performance (40). This decrease in blood lactate concentration in the placebo group is somewhat surprising and difficult to explain, but it could be related to a possible tapering effect caused by the training reduction and the absence of official handball games that took place during the intervention week of the study, which took place in the middle of a very demanding competitive season. On this assumption, it might be hypothesized that the absence of decrease in blood lactate observed in the Cr group during submaximal running suggests that Cr supplementation interfered with the development of endurance running observed in the placebo group during the administration period. However, the time to exhaustion observed during the endurance running test does not support a negative effect of Cr intake on endurance running because no differences in time to exhaustion were observed in either group after the supplementation period. Taking the submaximal and maximal responses observed during the maximal multistage discontinuous incremental running test together, it can be suggested that Cr supplementation did not result in any improvement in performance of endurance running exercise. Further research, including measuring performance during different types of aerobic exercise and a higher number of subjects are needed to evaluate the importance of Cr supplementation during endurance running exercise in trained subjects.

Cr supplementation led in the present study to an average increase of 0.6 kg in body mass, whereas it remained unaltered in the placebo group. With few exceptions, the majority of studies have reported increases in body mass of 0.5–3.0 kg after short-term Cr supplementation (4,24,27,33,37). A possible mechanism underlying short-term Cr-induced increase in body mass are increases in water retention in the intramuscular space (16) as a result of

the cellular transport of Cr with $Na^+$ (16). Some researches also suggests that the increased cellular hydration induced by short-term Cr supplementation might increase fat-free mass as a result of an enhanced myofibrillar protein synthesis or decreased protein degradation (4,37,38). However, the muscle enlargement induced by Cr supplementation seems to be more plausible in longer Cr-loading periods combined with strength-training programs (8,39).

Urinary creatinine excretion was significantly greater after 5 d of Cr supplementation when compared with placebo ingestion. Several studies have demonstrated that short-term Cr administration led to a significant increase in urinary creatinine excretion (16), although other studies did not find differences in creatinine elimination after Cr loading (24). The low amounts of Cr administered ($10 \, g \cdot d^{-1}$ instead of 20 $g \cdot d^{-1}$) (26) and the low number of subjects used ($N = 5$) (31) in the studies that did not demonstrate increases in urinary creatinine excretion may account for this discrepancy. Earlier studies demonstrated that there is no increase in urinary creatinine excretion until a significant amount of the administered Cr has been retained (5). Consequently, in the present study although muscular creatine (total muscle creatine and PCr) was not directly measured, the creatine-induced increases in urinary creatinine excretion and body mass observed after Cr loading indirectly suggests that Cr supplementation was effective in raising whole-body Cr stores.

In summary, the present results indicate that short-term Cr supplementation significantly improved lower-body maximal strength, maximal repetitive high-power exercise bouts, and total repetitions performed to fatigue during two sets of bench-press and half-squat actions in highly trained handball players. Creatine-supplemented handball players showed improved performance during the first 5 m of repeated bouts of 15-m sprint runs and attenuated decline in jumping ability after submaximal repetitive high-power-output half-squat exercise bout. Furthermore, the results show that Cr supplementation did not result in any improvement in performance of endurance running exercise.

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