Long-term creatine intake is beneficial to muscle performance during resistance training

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1Department of Kinesiology, Faculty of Physical Education and Physiotherapy, and 2Biomedical Nuclear Magnetic Resonance Unit, Department of Radiology, Faculty of Medicine, Katholieke Universiteit Leuven; and 3Department Rega School, Katholieke Hogeschool Leuven, B-3001 Leuven, Belgium

Vandenbergh, K., M. Goris, P. Van Hecke, M. Van Leemputte, L. Vangerven, and P. Hespel. Long-term creatine intake is beneficial to muscle performance during resistance training. J. Appl. Physiol. 83(6): 2055–2063, 1997.—The effects of oral creatine supplementation on muscle phosphocreatine (PCr) concentration, muscle strength, and body composition were investigated in young female volunteers (n = 19) during 10 wk of resistance training (3 h/wk). Compared with placebo, 4 days of high-dose creatine intake (20 g/day) increased (P < 0.05) muscle PCr concentration by 6%. Thereafter, this increase was maintained during 10 wk of training associated with low-dose creatine intake (5 g/day). Compared with placebo, maximal strength of the muscle groups trained, maximal intermittent exercise capacity of the arm flexors, and fat-free mass were increased 20–25, 10–25, and 6% more (P < 0.05), respectively, during creatine supplementation. Muscle PCr and strength, intermittent exercise capacity, and fat-free mass subsequently remained at a higher level in the creatine group than in the placebo group during 10 wk of detraining while low-dose creatine was continued. Finally, on cessation of creatine intake, muscle PCr in the creatine group returned to normal within 4 wk. It is concluded that long-term creatine supplementation enhances the progress of muscle strength during resistance training in sedentary females.

The effects of oral creatine supplementation on contractile performance and metabolism of skeletal muscle recently have become an area of major interest in exercise physiology. Thus evidence has accumulated over the last several years showing that short-term high-dose creatine intake may elevate muscle creatine stores, predominantly in its unphosphorylated form (6, 11, 14), and improve one's capacity to perform maximal intermittent exercise (2, 5, 6, 12, 24) but not a single bout of either high-intensity (7, 18, 19) or endurance type (1, 23) of exercise. The physiological mechanisms linking creatine loading to enhanced exercise performance remain, however, largely unexplained. While research to date mainly has focused attention on short-term effects of oral creatine ingestion, long-term oral creatine supplementation has developed as a widespread ergogenic practice among various categories of athletes. Yet the physiological impact of long-term creatine intake on the human body remains virtually unexplored. On the one hand, a recent study (15) has documented that the higher concentration of muscle creatine achieved after short-term creatine loading may be conserved for a period of 4 wk by continued creatine ingestion in a dosage equaling daily body creatine loss. On the other hand, fragmentary in vivo and in vitro evidence in literature suggest that creatine probably is needed for additional cellular functions than just phosphocreatine (PCr) production. Animals in which muscle creatine depletion was induced by feeding of creatine analogs have been shown to exhibit growth retardation and general weakness and at the same time to develop muscle ultrastructural abnormalities, including disruption of thin myofilaments, dilation of mitochondria, and disruption of Z bands (17, 20, 25, 28). Interestingly, such ultrastructural abnormalities resulting from abnormalities in creatine metabolism also have been associated with the incidence of muscular dystrophy or myopathy (27). Furthermore, on one hand, prolonged oral creatine supplementation has been shown to increase type II muscle fiber diameter (17) in patients with eye muscle atrophy. On the other hand, Earnest et al. (9) have reported that short-term creatine intake increases fat-free mass in strength-trained athletes. Accordingly, some (4, 16) but not all (10) in vitro findings indicate creatine stimulates the biosynthesis of muscle myosin. Given these earlier in vivo and in vitro findings, it is reasonable to speculate that oral creatine supplementation may exert an anabolic action in humans and thereby is likely to enhance the effects of resistance training on muscle mass and strength.

The aims of the present study, therefore, were 1) to evaluate whether creatine supplementation may add to the effects of resistance training on muscle strength and on the capacity to perform high-intensity exercise and 2) to evaluate the effects of long-term creatine supplementation on body composition.

METHODS

Subjects

Nineteen healthy, but sedentary, female subjects (no vegetarians) ranging in age from 19 to 22 yr gave their informed written consent to take part in the study. They were informed of the experimental procedures to be undertaken and were asked to abstain from any medication during the period of the study and to avoid changes in their diet or level of physical activity.

Study Protocol

A double-blind study was performed, in which the subjects first reported to the laboratory to become familiarized with
the intermittent arm flexor test and to measure their body weight. Subsequently subjects were assigned to either a creatine (Cr; n = 10) or a placebo (P; n = 9) group so as to obtain two similar groups with regard to muscle performance and body weight. In the first stage, the Cr group received 5 g of creatine monohydrate (2.5-g tablets) 4 times/day during 4 days (HD) while the P group received placebo supplements (5 g maltodextrine 4 times/day; 2.5-g tablets). Creatine and placebo tablets were identical in appearance and taste. This was followed by a period of 10 wk during which the Cr group consumed 2.5 g creatine monohydrate 2 times/day (LD). The P group continued on placebo (2.5 g maltodextrine 2 times/day). During the latter period, the subjects followed variable resistance training for 1 h three times per week. The training involved seven different exercises, including leg press, bench press, leg curl, leg extension, squat, shoulder press, and sit-ups. All training sessions were supervised by two physical education teachers, and the subjects maintained an individual training diary. Each exercise consisted of 5 series of 12 repetitions at 70% of one repetition maximum (1 RM). The 1-RM values were determined before and again after 5 and 10 wk of training. Before and after HD and after 5 and 10 wk of training combined with LD the subjects reported to the laboratory after a light standardized meal. 31P-nuclear magnetic resonance (NMR) spectroscopy of the gastrocnemius muscle of the right leg at rest was performed. The last training preceded these measurements by at least 2 days, and the last dose of creatine was ingested at least 2 h before the tests. Immediately after the NMR measurements, the subjects performed an intermittent exercise test with the right arm on an isokinetic dynamometer to evaluate the dynamic strength and fatigability of the arm-flexion muscles. Furthermore, body composition was assessed before HD and after 5 and 10 wk of training plus LD. Over the different experimental conditions, the subjects were evaluated at the same time of the day and on the same day of the week. Furthermore, 24-h urine samples were collected before, during the first and third days of HD, and after 10 wk of training plus LD. Finally, before and after 5 and 10 wk of training plus LD the subjects recorded their dietary food and drink intake for a period of 3 consecutive days by using Nutricia food-record questionnaires. They were instructed to eat as usual but to record as accurately as possible the quantity and type of food consumed.

At the end of the training plus LD period, a subgroup of subjects (n = 13) agreed to continue for an additional 10-wk detraining period. Thus training was stopped, but LD supplementation was continued for 10 wk both in Cr (n = 7) and P (n = 6) groups. At the end of this period, LD supplementation was stopped. After 3 and 10 wk of LD and 1 and 4 wk after cessation of the this supplementation, NMR spectroscopy of the gastrocnemius muscle and the intermittent arm-flexion test on the isokinetic dynamometer were repeated. Furthermore, densitometry measurements were performed after 3 and 10 wk LD and 4 wk after the LD period. The results of the measurements were not disclosed either to the subjects or to the investigators until completion of the entire study.

**Determination of Muscle PCr Concentration**

31P-NMR measurements from the calf muscles were performed in a 4.7-T superconducting magnet with 30-cm-diameter horizontal bore ( Biospec, Bruker, Karlsruhe, Germany). Before the leg was inserted into the magnet, the calf was marked at the level of its largest circumference. The mark was then positioned in the center of a 50-mm-diameter surface coil, mounted in a wooden mold, with an adjustable footholder allowing accurate and reproducible positioning of each of the subjects’ legs during the different NMR sessions.

The coil was tuned to either the proton or the phosphorous frequency. Axial proton NMR images (200 MHz) were acquired with the surface coil to verify the position of the muscle on the coil (Flash sequence with repetition time/echo time/angle = 100 ms/10 ms/40°; three slices, 10 mm thick, 10-mm gap). 31P-NMR (81.1 MHz) signals were acquired with a 160-µs excitation pulse (corresponding to an angle of ~120° in the middle of the coil) and accumulated to improve the signal-to-noise ratio (64 acquisitions, every 5 s). The time-domain NMR signals were exponentially filtered (5-Hz line broadening) to improve the signal-to-noise ratio and were Fourier transformed for spectral analysis. Finally, the PCr and ATP peaks were manually integrated. Integral values were corrected for partial saturation due to incomplete relaxation during the 5-s repetition period (correction factor 1.36 for PCr and 1.08 for β-ATP). Correction factors were determined from a separate measurement on a single subject by comparing the partially relaxed spectrum (5-s repetition period) with a fully relaxed spectrum (50-s repetition period).

Because β-ATP peak areas were unchanged over the different treatments, the mean area for β-ATP calculated from all repeated measurements performed in the total group of subjects was set equivalent to a concentration of 5.5 mmol/kg wet muscle (13). Thereafter, individual β-ATP areas were referred to this mean ATP value, and ATP concentrations were expressed in millimoles per kilogram wet muscle. PCr concentrations were calculated by multiplying the ratio of the saturation corrected peak areas of PCr to ATP by the ATP concentration.

**Determination of Arm-Flexion Torque**

The exercise test consisted of the subjects performing unilateral arm flexions with their right arm while they were in a sitting position on an isokinetic dynamometer that was calibrated before each experiment. The dynamometer consisted of a computer-controlled asynchronous electromotor (AMK Dynasyn, 19 kW), instrumented with a torque transducer (Lebow, maximal torque 565 Nm, 0.05%). After a standardized 5-min warm-up the subjects performed 5 bouts of 30 dynamic maximal voluntary contractions of the arm flexor muscles separated by 2-min rest intervals. Arm-flexion torque was measured during each contraction and digitized (250 Hz) by an on-line computer. The dynamic torque was calculated as the mean torque during maximal arm flexion at a constant velocity of 180°/s, starting from 160 to 70° arm flexion. After each contraction the arm was returned (180°) passively to the starting position from which the next contraction was immediately initiated. Torque production was registered as the mean of five successive contractions.

**Body Composition**

Body composition was assessed by the hydrostatic-weighing method. Simultaneously, residual lung volume was measured by the helium-dilution technique. In the body density calculation, a correction of 150 ml was made for the gastrointestinal tract volume. Density was converted to percent body fat by using Siri’s equation (22): fat = (4.95/density – 4.50) × 100.

**Analyses and Statistics**

The dietary questionnaires were coded and analyzed for energy content and carbohydrate, fat, and protein composition by using the Nutricia dietary analysis software. Urinary creatine, creatinine, urea, and urate excretion were
determined by standard enzymatic methods (3). The results are expressed as means ± SE. Statistical evaluation was performed by using unpaired t-tests and repeated-measures two-way analysis of variance (SAS Institute, general linear models procedure) by using Scheffé’s tests for post hoc multiple comparisons, where appropriate. The level of statistical significance was set at P < 0.05.

RESULTS

Treatment Identification, Nutritional Data, and Side Effects

At the end of the experimental period the subjects were asked whether they were aware of the treatment they had received. After either creatine or placebo treatment, all subjects reported that they were unsure they had received. After either creatine or placebo were asked whether they were aware of the treatment for further analyses of the treatment effects. Thus, as fore, mean torque production per series was considered.

Effects of 4 Days of HD Supplementation

Muscle ATP and PCr. NMR spectroscopy PCr/ATP peak ratios and the calculated ATP and PCr concentrations of the gastrocnemius muscle before and after 4 days of HD creatine or placebo are presented in Table 1. Baseline values for muscle ATP and PCr concentrations and PCr/ATP ratios were similar in Cr and P subjects. Muscle ATP concentration was not changed by HD. However, compared with the P group, the Cr group increased (P < 0.05) muscle PCr/ATP ratio and PCr concentration. The increase in PCr in the Cr group, relative to the change in the P group, amounted to 6% during HD.

Arm-flexion torque. Five series (S1–S5) of 30 maximal voluntary dynamic arm flexions separated by 2-min rest intervals, were performed. The pattern of fatigue typical to this exercise test is shown in Fig. 1. The data points represent the average torque value of five consecutive contractions before and after HD in both the P and Cr groups. Within each series, torque peaked at the start, whereafter it progressively declined. Compared with the peak torque observed at the start of S1, torque was ~15, 18, 23, and 23% lower at the start of S2, S3, S4, and S5, respectively. Torque produced at the end of S1, S2, S3, S4, and S5 represented on the average 63, 54, 51, 49, and 49% of S1 peak torque, respectively. Baseline values were not significantly different between the P and Cr groups. As indicated above, within each series of 30 arm flexions, torque progressively decreased. The slope of this decrease was not significantly altered by creatine. Therefore, mean torque production per series was considered for further analyses of the treatment effects. Thus, as shown in Fig. 2A and compared with the pretest, posttest torques slightly increased in the Cr group, whereas they slightly decreased in the P group. However, changes (post-HD minus pre-HD) were not significantly different between the two groups (P < 0.05).

Urinary measurements. Table 2 summarizes data from 24-h urine collections before and during the first and third day of HD. Urinary volume was on the average 1,350 ± 62 ml and was not different between groups on either day. Twenty-four-hour urinary creatine, creatinine, urea, and urate excretions during placebo were in the normal range for all subjects. The Cr group increased (P < 0.05) urinary creatine excretion from the milligram range to ~7 and 11 g/day during the first and third day of creatine, respectively. In addition, compared with placebo, creatine slightly raised (P < 0.05) 24-h urinary creatinine excretion. Thus total urinary creatinine excretion (creatinine + creatine) was calculated to amount to ~8 and 12 g/24 h during the first and third day of creatine, respectively (P < 0.05 vs. placebo). Twenty-four-hour urinary urea and urate excretions were within the normal physiological range during HD. However, compared with the P group, slightly higher (P < 0.05) urate excretions were measured in the Cr group.

Body composition. Densitometry was performed at the start but not at the end of HD. In the P group, body weight, percent body fat, and fat-free mass were 58 ± 3 kg, 25 ± 1%, and 43 ± 1 kg, respectively. Corresponding values were similar in the Cr group (see Table 3).

Table 1. Muscle ATP and PCr concentration and PCr/ATP ratio at rest before and after 4 days of high-dose supplementation and after 5 and 10 wk of low-dose supplementation of creatine or placebo in combination with resistance training

<table>
<thead>
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<th>Pre</th>
<th>4 days</th>
<th>5 wk</th>
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<tr>
<td>ATP, mmol/kg wet wt</td>
<td>5.5 ± 0.2</td>
<td>5.6 ± 0.2</td>
<td>5.7 ± 0.3</td>
<td>5.4 ± 0.3</td>
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<td>Placebo group</td>
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<td>Creatine group</td>
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<td>PCr, mmol/kg wet wt</td>
<td>5.6 ± 0.2</td>
<td>5.4 ± 0.2</td>
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<td>Placebo group</td>
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<td>Creatine group</td>
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<tr>
<td>PCr/ATP</td>
<td>23.0 ± 0.5</td>
<td>24.2 ± 0.8*</td>
<td>24.5 ± 1.2*</td>
<td>24.2 ± 1.1*</td>
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<tr>
<td>Placebo group</td>
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<tr>
<td>Creatine group</td>
<td>4.1 ± 0.1</td>
<td>4.0 ± 0.1</td>
<td>3.9 ± 0.1</td>
<td>4.2 ± 0.1</td>
</tr>
<tr>
<td>PCr/ATP</td>
<td>4.1 ± 0.1</td>
<td>4.5 ± 0.2*</td>
<td>4.5 ± 0.2*</td>
<td>4.5 ± 0.1*</td>
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Values are means ± SE of 9 subjects in placebo group and 10 subjects in creatine group. Saturation-corrected phosphocreatine (PCr) ATP ratio was calculated from individual spectra before (Pre) and after 4 days of high-dose placebo and creatine (20 g/day) administration and after 5 and 10 wk of low-dose placebo and creatine administration (5 g/day) in combination with resistance training (3 times/week). ATP and PCr concentrations were calculated assuming mean β-ATP peak area to correspond to ATP concentration of 5.5 mmol/kg wet muscle. See METHODS for further details. *Significantly different treatment effect compared with placebo, P < 0.05.
Effects of 10 wk of Resistance Training in Combination with LD Supplementation

Maximal muscle strength. 1 RM of leg press, bench press, leg curl, leg extension, squat, and shoulder press were determined before and after 5 and 10 wk of resistance training in combination with LD (Table 4). During placebo, 1 RM of 3 exercises (leg extension, squat, and shoulder press) was significantly increased (+15 to +40%; P < 0.05) after 5 wk, whereas all 1 RM values were increased (from +25 to +57%; P < 0.05) after 10 wk of training plus LD. However, in the Cr group, 5 wk of training plus LD were sufficient to significantly increase (from +16 to +56%; P < 0.05) 1 RM of all exercises. Compared with placebo, 1 RM increments for leg press, leg extension, and squat produced by the 10-wk training period were 20–25% greater (P < 0.05) during creatine and also tended to be greater (P < 0.15) for bench press and leg curl. No significant differences were seen between the P and Cr groups in strength gain for shoulder press.

Muscle ATP and PCr. Muscle ATP concentration was not changed by resistance training plus LD (Table 1). The higher muscle PCr/ATP ratio due to higher PCr concentration achieved after HD in the Cr group was maintained (P < 0.05) after 5 and 10 wk of resistance training combined with LD. The increase in muscle PCr after 5 and 10 wk of LD in the Cr group, relative to the P group, amounted to 7 and 10% of the initial concentration, respectively.

Arm-flexion torque. Compared with the P group, 5 wk of training plus LD increased (P < 0.05) arm torque production in the Cr group (Fig. 2B). This effect was even more pronounced after 10 wk of LD, when arm-flexion torque was 11, 18, 20, 21, and 25% higher (P < 0.05) during S1, S2, S3, S4, and S5, respectively, in the Cr group than in the P group (Fig. 2C).

Urinary measurements. As shown in Table 2, in the Cr group, 24-h urinary creatine excretion at the end of the training plus LD period was ~4 g (P < 0.05 vs. P group). Creatinine excretion in the Cr group was in the normal range but tended to be higher compared with the P group (P = 0.07). Thus total urinary creatine excretion (creatinine + creatine) in the Cr group amounted to ~5 g/day (P < 0.05 vs. P). Twenty-four-hour urinary urea and urate excretions were normal and similar in the Cr and P groups.

Body composition. Compared with initial values, fat-free mass was increased more (P < 0.05) in the Cr group than in the P group after both 5 (Cr group: +4.5%; P group: +2.5%) and 10 wk (Cr group: +5.8%; P group: +3.7%) of training plus LD (Table 3). Body weight tended to increase (P = 0.12), whereas percent body fat tended to decrease (P = 0.14) during the training plus LD period, but these changes were not significantly different between the P and Cr groups.

Effects of Detraining and Cessation of Supplementation

After the 10 wk of resistance training in combination with LD, a subgroup of subjects (P group: n = 6; Cr group: n = 7) was first followed during a period of 10 wk after discontinuation of training (detraining) while LD supplementation (5 g/day) was continued. Thereafter, LD was also stopped, and subjects were studied during an additional 4-wk period. The pattern of changes in NMR measurements, torque production during the intermittent arm-flexion test, training-induced 1-RM changes, and urinary and densitometry measurements during HD and during training combined with LD supplementation in this subgroup of subjects were similar to the total group of subjects.

Muscle ATP and PCr. Muscle ATP concentration was not changed by LD. As shown in Fig. 3, during the entire detraining plus LD period, muscle PCr concentration stayed at a higher level (P < 0.05) in Cr than in P subjects. When LD was stopped, the higher PCr concentration in the Cr group compared with the P group, faded toward the end of the 4-wk follow-up period.
Arm-flexion torque. Figure 4 shows the changes in arm power output in this subgroup throughout the entire study. For reasons of clarity, data points represent the average torque output generated during the entire maximal intermittent arm flexion test (S1-S5). During detraining plus LD, power output decreased at the same rate in P and Cr subjects. Yet, compared with the P group, because of the higher power level achieved after training plus LD, torque remained higher in the Cr group after both 3 and 10 wk of detraining plus LD and continued to remain higher even 1 wk after cessation of LD. After 4 wk without LD supplementation, however, torque production during the arm-flexion test was similar in the P and Cr groups.

Body composition. The increase in fat-free mass achieved in the Cr group at the end of the resistance training plus LD period was maintained throughout the detraining plus LD period (Fig. 5). Even 4 wk after cessation of LD, compared with placebo, fat-free mass was still greater in Cr than in P subjects. Changes in weight and percent fat were similar between groups during and after detraining plus LD.

DISCUSSION

Over the last 5 yr, exercise physiology has focused considerable attention on the effects of oral creatine supplementation on human exercise performance. During this period it has been clearly established that high-dose (~20 g/day) oral creatine intake for a period of 5–6 days may elevate muscle creatine and PCr stores (6, 11, 14, 15, 24). Furthermore, creatine loading has been shown to improve performance during high-intensity intermittent exercise (2, 5, 6, 12, 24) but not to be beneficial to single bouts of various modes of exercise (1, 7, 18, 19, 23). Meanwhile, creatine loading by athletes is being done ahead of the scientific evidence. Thus despite the fact that just some short-term effects of creatine supplementation have been described, long-term creatine loading is rapidly developing as a standard ergogenic practice in various categories of athletes. Given the need for long-term observations in this area, and the suggested possibility that creatine might exert an anabolic action in skeletal muscle, it was investigated here whether prolonged creatine intake is able to enhance the effects of resistance training on muscle strength. The data presented clearly demonstrate that long-term creatine supplementation increases body fat-free mass and at the same time adds to the beneficial effects of resistance training on muscle strength.

The potential of creatine to stimulate protein synthesis in skeletal muscle was first recognized by Ingwall (16) over 20 yr ago. In this study, Ingwall observed that the addition of creatine to incubated skeletal muscle cells in vitro resulted in enhanced myosin synthesis. In keeping with these in vitro observations, Sipilä et al. (21) and Vannas-Sulonen et al. (26) have reported peripheral type II muscle hypertrophy and improved peripheral muscle strength occurred as side effects in gyrate atrophy patients treated with low-dose creatine (1.5 g/day) for a period of 1–5 yr. In addition, these beneficial muscular changes were found to disappear on discontinuation of the treatment. Furthermore, 1 mo of creatine intake recently was reported to improve muscle strength and increase body fat-free mass in strength-trained athletes (9). In line with these earlier observations, the present double-blind intervention study shows that 10 wk of resistance training in young female volunteers caused a markedly greater increment in both maximal muscle strength and maximal intermittent arm power output (see Figs. 2 and 4) when creatine was ingested during the training period. Several mechanisms may be considered to explain this beneficial effect of creatine. First, it is likely that higher training workload was a prime mechanism contributing to the greater training progress in subjects on creatine, particularly during the second half of the training period. Thus training workloads were identi-
cal in the two groups during the initial 5 wk of training. Still, fat-free mass (see Table 3 and Fig. 5) and maximal muscle strength (see Table 4) were found to be markedly enhanced in the Cr group. However, during the second half of the training period, absolute training intensity for most exercises was higher in Cr subjects, because after 5 wk the training workload was adjusted to their higher 1 RM achieved. Second, our findings suggest that creatine supplementation might allow optimal training to continue for a longer period before overtraining develops. Indeed, in controls, on one hand, maximal muscle strength (see Table 4) improved from the start to the end of the 10-wk training period, but, on the other hand, maximal intermittent exercise capacity of the arm flexors was found to deteriorate between 5 and 10 wk of training (see Fig. 2), which may indicate some degree of overtraining. Conversely in the Cr group, not only was the increment of muscle strength greater throughout the study but also intermittent exercise capacity continued to increase during the second phase of the training program. Third, compared with placebo, body fat-free mass was over the training period found to increase ~60% more during creatine loading. In this respect it must, however, be emphasized that this increase may at least partly result from increased muscle water content (15). However, in con-
cert with the aforementioned in vivo (21, 26) and in vitro observations (16) and the greater muscle strength observed here, this might also indicate that creatine supplementation, indeed, facilitates the development of muscle hypertrophy during resistance training. Thus the better training response with creatine intake may be due to the concerted action of higher training load, reduced training fatigue, and possibly accelerated muscle hypertrophy.

Another present interest in creatine research is whether the known effects of short-term high-dose creatine loading (2, 5, 6, 12, 24) may be conserved by continued low-dose creatine intake. In this respect a recent report (15) already has indicated that the elevated muscle creatine store generated by 6 days of creatine loading (20 g/day) is maintained for a period of 1 mo by a dosage of 2 g creatine/day. Accordingly, in the present study the higher concentration of muscle PCr achieved after 4 days of HD supplementation was maintained during the 10-wk training period combined with daily low-dose creatine ingestion (5 g). Furthermore, when creatine supplementation was continued for 10 wk after cessation of training, muscle PCr stores remained at the higher level. However, within 4 wk after creatine supplementation was stopped, muscle PCr regressed to baseline values.

An interesting issue also is whether creatine supplementation might diminish regression of acquired strength on cessation of resistance training. In this respect, our present data obtained in the subgroup of subjects further followed during detraining after the 10-wk resistance training period show that continuation of creatine supplementation did not prevent arm power output from returning to the pretraining level. This may, however, be at least partly explained by blunted motivation caused by the strenuous training program, as indicated by the exaggerated fall of arm torque to below baseline in subjects on placebo (see Fig. 4). However, the higher level of intermittent arm torque production achieved at the end of the training period in Cr subjects was maintained throughout the

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Fig. 3. Change in muscle phosphocreatine concentration ($\Delta$PCr) before and after long-term creatine supplementation. Values are means ± SE of 6 subjects in placebo and 7 subjects in creatine group. Data points represent change in $^{31}$P-nuclear magnetic resonance PCr values measured in medial head of gastrocnemius muscle at rest, produced by 4 days of high-dose supplementation (HD; 20 g/day), followed by 10 wk of resistance training in combination with low-dose supplementation (training + LD; 5 g/day), followed by 10 wk of low-dose (LD; 5 g/day) placebo (C) or creatine (Cr) administration after cessation of training, and finally cessation of supplementation for 4 wk. See METHODS for further details. *Significant treatment effect compared with placebo, P < 0.05.

Fig. 4. Effect of long-term creatine supplementation on dynamic arm-flexion torque during maximal intermittent exercise. Data points represent mean torque per entire arm-flexion test. Values are means ± SE of 6 subjects in placebo group and 7 subjects in creatine group and represent change in arm-flexion torque produced by 4 days of HD supplementation (20 g/day), followed by 10 wk of training + LD supplementation (5 g/day), followed by 10 wk of LD (5 g/day) placebo (C) or creatine (Cr) administration after cessation of training, and finally cessation of supplementation for 4 wk. Five series of 30 dynamic arm flexions were performed, by using an isokinetic dynamometer, with rest intervals of 2 min between the series. See METHODS for further details. *Significant treatment effect compared with placebo, P < 0.05.

Fig. 5. Effect of long-term creatine supplementation on fat-free mass. Values are means ± SE of 6 subjects in placebo group and 7 subjects in creatine group and represent change in fat-free mass produced by 4 days of HD supplementation (20 g/day) followed by 10 wk of training + LD supplementation (5 g/day), followed by 10 wk of low-dose (LD; 5 g/day) placebo (C) or creatine (Cr) administration after cessation of training, and finally cessation of supplementation for 4 wk. Fat-free mass was assessed by the hydrostatic-weighing method. See METHODS for further details. *Significant treatment effect compared with placebo, P < 0.05.
detraining period. Only 4 wk after cessation of creatine ingestion did arm torque in the Cr group return to placebo level. This suggests that creatine supplementation, indeed, may have the potential to alleviate regression of muscle strength after discontinuation of resistance training.

A final point of consideration is the absorption and excretion of oral creatine during and after supplementation. In this respect, an early study has indicated that only ~30% of creatine ingested during high-dose supplementation is absorbed during the initial 2 days of intake, decreasing to <15% after 2 or more days (14). In fact the bulk of creatine ingested at high dosage is excreted in the form of urinary creatine, with only a minor fraction appearing as urinary creatinine. Accordingly, in the present study urinary creatinine excretion during placebo was in the predicted range of 1.1–1.2 g/24 h indicating adequate urine collection (8) and was only slightly increased by creatine intake. However, estimated creatine absorption during high-dose (20 g/day) creatine loading amounted to 60 and 40% of the dose ingested during the first and third day, respectively, which is markedly higher than previously reported values in a small number (n = 4) of subjects (14). At the end of the 10-wk training period combined with low-dose creatine intake total urinary creatine excretion was equal to the creatine dosage (5 g/day), which suggests that inhibition of endogenous creatine synthesis had developed. Unfortunately, urine collections could not be performed during the 10-wk detraining period. Yet, on cessation of the 21-wk creatine supplementation period muscle PCr concentration had returned to normal values. In conclusion, the present study demonstrates oral creatine supplementation on performance during repeated bouts of maximal isokinetic cycling in man. Eur. J. Appl. Physiol. 69: 268–270, 1994.

REFERENCES


