Creatine ingestion favorably affects performance and muscle metabolism during maximal exercise in humans

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Casey, A., D. Constantin-Teodosiu, S. Howell, E. Hultman, and P. L. Greenhaff. Creatine ingestion favorably affects performance and muscle metabolism during maximal exercise in humans. Am. J. Physiol. 271 (Endocrinol. Metab. 34): E31–E37, 1996.—Nine male subjects performed two bouts of 30-s maximal isokinetic cycling before and after ingestion of 20 g creatine (Cr) monohydrate/day for 5 days. Cr ingestion produced a 23.1 ± 4.7 mmol/kg dry matter increase in the muscle total creatine (TCr) concentration. Total work production during bouts 1 and 2 increased by ~4% and the cumulative increases in both peak and total work production over the two exercise bouts were positively correlated with the increase in muscle TCr. Cumulative loss of ATP was 30.7 ± 12.2% less after Cr ingestion, despite the increase in muscle torque/work production. Resting phosphocreatine (PCr) increased in type I and II fibers. Changes in PCr before exercise bouts 1 and 2 in type II fibers were positively correlated with changes in PCr degradation during exercise in this fiber type and changes in total work production. The results suggest that improvements in performance were mediated via improved ATP resynthesis as a consequence of increased PCr availability in type II fibers.

phosphocreatine; adenosine 5'-triphosphate; muscle fiber types

FATIGUE SUSTAINED DURING short-term maximal-intensity exercise in humans has been associated with the inability of skeletal muscle to maintain a high rate of anaerobic ATP production from phosphocreatine (PCr) hydrolysis (6, 18, 21). Furthermore, evidence is also available to suggest that fatigue under these conditions may be attributable to an impairment of ATP production predominantly in type II muscle fibers, in which the PCr concentration is rapidly depleted (7a, 25).

Harris et al. (16) were the first to demonstrate that ingestion of 5 g creatine (Cr) monohydrate on four to six occasions each day for several consecutive days could increase the total creatine (TCr; ΣPCr and Cr) concentration of human skeletal muscle by an average of 25 mmol/kg dry matter, some 30% of which occurred in phosphorylated form as PCr. The authors went on to suggest that these changes might have a beneficial effect on exercise performance in humans, and indeed recent placebo controlled studies, using a variety of experimental models, have confirmed that dietary Cr supplementation can improve exercise performance during repeated bouts of maximal-intensity exercise (1, 5, 8, 12, 17).

To date, there has been no direct investigation of the effects of Cr ingestion on muscle metabolism during maximal-intensity dynamic exercise. However, several of the performance studies cited above found a reduction in plasma ammonia (5, 12) and hypoxanthine (1) accumulation during exercise after Cr ingestion, despite increases in muscle torque/work production. As a consequence of these findings, the ergogenic effect of Cr ingestion was attributed to possible improvements in the ability of muscle to sustain ATP rephosphorylation from ADP during exercise, which may have been achieved as a result of an increase in preexercise PCr availability, an improvement in muscle buffering capacity, and/or an acceleration of PCr resynthesis during exercise and recovery. In support of this latter hypothesis, acceleration of PCr resynthesis during recovery from intense electrically evoked isometric muscle contraction has been shown to occur after Cr supplementation (11). Whether a similar relationship exists between Cr availability and changes in metabolism during maximal dynamic exercise of short duration has yet to be ascertained.

The studies of Harris et al. (16) and Greenhaff et al. (11) also drew attention to the large interindividual variation in the change in muscle TCr concentration, which appeared to be at least partly related to the initial TCr concentration of the muscle. However, perhaps more importantly, Greenhaff et al. (11) showed that a measurable effect of Cr ingestion on PCr resynthesis during recovery from maximal-intensity exercise was only observed in individuals who demonstrated more than a 20 mmol/kg dry matter increase in muscle TCr concentration after Cr ingestion. These results suggest that a favorable effect of Cr ingestion on metabolism and performance during exercise and recovery may be critically dependent on the magnitude of the increase in muscle TCr concentration during supplementation.

The aim of the present experiment, therefore, was to perform a direct investigation of the effects of Cr supplementation on skeletal muscle energy metabolism and performance during repeated bouts of maximal exercise in humans. It was hypothesised that 1) a relationship would exist between increases in muscle Cr availability and improvements in maximal dynamic exercise performance and 2) that, since fatigue during maximal exercise is associated with a fall in ATP resynthesis from PCr degradation in type II muscle fibers (7a, 25), an increase in type II fiber PCr availability might improve the maintenance of force production via an effect on ATP resynthesis.

METHODS

Subjects. Nine healthy male subjects gave their written consent to take part in the present study, which was approved by the University of Nottingham Medical School Ethical...
Committee. The level of fitness of the subjects was assessed by means of their training diaries. All subjects were well trained in the sense that they trained 5–6 days/wk on a regular basis, and all competed in various sports to a good club level. Mean (±SE) age, height, and weight were 27 ± 1 yr, 185 ± 2 cm, and 78 ± 2 kg, respectively. Before beginning the study, all subjects participated in a routine medical examination.

Experimental protocol. On the first visit to the laboratory, subjects were thoroughly familiarized with maximal-intensity isokinetic cycling and all procedures involved in the experiment. All subjects then reported back to the laboratory after an overnight fast on four further occasions, having been instructed to abstain from strenuous physical activity and alcohol intake for 24 h, from caffeine intake on the day of each experiment, and having maintained dietary intake to as close to normal as possible.

On the first occasion, subjects performed two bouts of 30-s maximal-intensity isokinetic cycling. Each bout of exercise was performed at 80 revolutions/min and was separated by 4 min of passive recovery during which subjects rested on a couch. This protocol was repeated on a second visit, separated from the first by 5 days, to assess reproducibility of total work production. Subjects in whom measurements of total work production differed by >5% were recalled and were required to repeat the procedure. At the end of this period of familiarization, measurements of total work production during exercise, measured over a period of 1 wk, differed by 2.6 ± 0.5% (n = 9 subjects).

On a third visit, all subjects repeated the two bouts of maximal-intensity exercise again; however, on this occasion, muscle biopsy samples were obtained from the vastus lateralis (2) immediately before and after each bout of exercise. All biopsies were obtained from one limb that was chosen at random before the start of the study and were obtained while the subjects remained seated on the cycle ergometer, with the exception of the initial resting biopsy, which was obtained with subjects resting on a couch. Two days later, subjects proceeded to consume 20 g Cr/day (Cairns Chemicals, Chesham, UK) for five consecutive days. All subjects were instructed to consume 5 g Cr, dissolved in 250 ml of a warm-hot beverage, on four occasions at equally spaced intervals. The morning after the final day of Cr ingestion, subjects reported back to the laboratory on a final occasion and repeated the exercise procedures that they had previously performed. Likewise, muscle biopsy samples were obtained immediately before and after each bout of exercise, but on this occasion the contralateral limb was used.

Measurements of average work production per pedal revolution (J) and total work production (J/kg body mass) were obtained as described in the accompanying paper (8a). Peak work production refers to the maximum value obtained during 30 s of exercise.

Muscle sampling and analysis. Sampling and analytic procedures are described in the accompanying paper (8a). In the present study, ATP, PCr, Cr, glucose 6-phosphate (G-6-P), and lactate concentrations were measured spectrophotometrically in mixed muscle (14). Of the total number of individual muscle fibers dissected, the amount successfully classified as type I or type II was 88 ± 1%. Mean pooled weight of the type I and type II fibers was 21.2 ± 0.6 and 22.8 ± 0.5 μg, respectively. PCr concentrations in type I and type II fibers were measured using a fluorimetric modification of the method of Harris et al. (14).

Statistical analysis. All exercise performance data refer to n = 9 subjects. Muscle metabolite data presented in the text, Tables 1 and 2, and Figs. 1–5 before Cr ingestion refer to n = 9 subjects and post-Cr ingestion to n = 8 or 7 subjects. This is because, after Cr ingestion, it was not possible to obtain postexercise biopsy samples from one subject, and a second subject chose not to have any biopsy samples taken.

Differences in peak and total work production, and muscle metabolite concentrations (both absolute and Δ values) during each bout of exercise pre- and post-Cr supplementation were examined using repeated measures analysis of variance (BMDP 2V/5V), with experimental condition (pre- and post-Cr) and time (number of consecutive exercise bouts) as factors. This software allows unbalanced analysis of variance to be performed on incomplete data sets without estimation of the missing data. Scheffe’s test for comparing mean values was used as a post hoc test when significant interactions were detected.

Relationships between variables were examined by computing the Pearson product-moment correlation coefficient (r). Statistical significance was accepted at the 5% level (P < 0.05). Values are presented in the text, Tables 1 and 2, and in Figs. 1–5 as means ± SE.

RESULTS

Muscle torque production. Peak work production was recorded within 1.8 ± 0.2 s of exercise and is shown in Fig. 1A. After Cr ingestion, seven of the nine subjects showed an improvement in peak work production during bouts 1 and 2, but a statistical difference was not quite achieved (4.1 ± 2.0 and 3.8 ± 1.7%, respectively; P = 0.052). Figure 1B shows total work production (J/kg body mass) during exercise bouts 1 and 2 before and after Cr ingestion. After Cr ingestion, total work
Creatine and Muscle Metabolism

Table 1. Mixed-muscle ATP, PCr, Cr, TCr (ΣPCr and Cr), G-6-P, and lactate concentrations measured immediately before and after 2 bouts of 30 s maximal-intensity isokinetic cycling exercise

<table>
<thead>
<tr>
<th></th>
<th>Pre-Cr Ingestion</th>
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<th>Post-Cr Ingestion</th>
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<tr>
<td>ATP</td>
<td>23.9 ± 0.4</td>
<td>18.7 ± 1.3*</td>
<td>20.7 ± 1.4</td>
<td>17.3 ± 1.0*</td>
<td>23.3 ± 0.5</td>
<td>18.7 ± 1.2*</td>
<td>19.4 ± 1.3</td>
<td>17.9 ± 1.3</td>
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<tr>
<td>PCr</td>
<td>83.9 ± 3.6</td>
<td>34.8 ± 4.5*</td>
<td>72.8 ± 3.0</td>
<td>24.2 ± 1.9*</td>
<td>92.3 ± 1.8†</td>
<td>36.0 ± 3.1*</td>
<td>75.3 ± 3.1</td>
<td>27.9 ± 4.5*</td>
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<td>Cr</td>
<td>43.6 ± 0.9</td>
<td>92.4 ± 7.1*</td>
<td>55.0 ± 5.7</td>
<td>98.6 ± 3.9*</td>
<td>60.0 ± 3.1†</td>
<td>113.4 ± 8.1†</td>
<td>72.2 ± 5.6†</td>
<td>124.9 ± 7.3†</td>
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<tr>
<td>TCr</td>
<td>177.7 ± 3.4</td>
<td>199.8 ± 4.9</td>
<td>197.8 ± 4.1</td>
<td>192.5 ± 3.8</td>
<td>151.6 ± 4.3†</td>
<td>148.4 ± 5.5†</td>
<td>147.5 ± 4.5†</td>
<td>152.8 ± 6.8†</td>
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<tr>
<td>G-6-P</td>
<td>2.5 ± 0.9</td>
<td>21.6 ± 2.6*</td>
<td>6.4 ± 1.9</td>
<td>17.0 ± 2.0*</td>
<td>1.9 ± 0.2</td>
<td>20.9 ± 2.0*</td>
<td>8.1 ± 1.6</td>
<td>17.6 ± 1.5*</td>
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<tr>
<td>Lactate</td>
<td>4.4 ± 0.5</td>
<td>90.0 ± 13.0*</td>
<td>49.7 ± 9.8</td>
<td>127.7 ± 10.3*</td>
<td>3.9 ± 0.7</td>
<td>86.1 ± 12.3*</td>
<td>49.7 ± 9.5</td>
<td>115.5 ± 11.8*</td>
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Values are means ± SE in mmol/kg dry matter. PCr, phosphocreatine; Cr, creatine; TCr, total creatine; G-6-P, glucose 6-phosphate; B1, bout 1; B2, bout 2. Each bout of exercise was performed at 80 revolutions/min and was separated by 4 min of recovery. Values are given precreatine and postcreatine supplementation for 5 days (4 × 5 g/day). *Significant differences pre- and postexercise (P < 0.01). †Significant differences between corresponding concentrations pre- and post-Cr ingestion (P < 0.05).

Production increased by 11.6 ± 3.1 J/kg body mass (4.2 ± 1.1%; P < 0.05) and 10.9 ± 2.9 J/kg body mass (4.4 ± 1.2%; P < 0.05) in exercise bouts 1 and 2, respectively. Irrespective of treatment, total work production was always greatest during the first bout of exercise (P < 0.01).

Mixed-muscle metabolites. Table 1 shows mixed-muscle metabolite concentrations before and after exercise bouts 1 and 2, pre- and post-Cr ingestion. Cr ingestion resulted in a 23.1 ± 4.7 mmol/kg dry matter (18.5 ± 3.9%; P < 0.05) increase in muscle TCr concentration, of which ~1/3 was in the form of PCr (8.4 ± 4.4 mmol/kg dry matter, P < 0.05; range -3.2 to 26.9 mmol/kg dry matter) and the remainder in the form of Cr (16.5 ± 3.4 mmol/kg dry matter, P < 0.05; range 3.8–27.4 mmol/kg dry matter). The individual increases in muscle TCr concentration after Cr supplementation are shown in Fig. 2, in which subjects have been numbered one to eight, according to their initial muscle TCr concentration. This figure demonstrates that interindividual variation in the increase in muscle TCr concentration was large, ranging from 6.4 to 37.8 mmol/kg dry matter. Figure 3 shows increases in muscle TCr concentration as a result of Cr supplementation with reference to cumulative changes in peak and total work production over the two exercise bouts.

Fig. 2. Mixed-muscle total creatine (TCr; Σphosphocreatine and creatine) concentration in individual subjects precreatine and postcreatine supplementation for 5 days (4 × 5 g/day). Values represent the mean of biopsies obtained before and after 2 bouts of 30-s maximal-intensity isokinetic cycling exercise (n = 4) precreatine and postcreatine supplementation. Subjects have been numbered 1–8 based on their initial muscle TCr concentration.

Fig. 3. Relationship between individual changes in mixed-muscle total creatine (Σphosphocreatine and creatine) concentration and cumulative changes in peak (r = 0.71, P < 0.05; A, y = -0.65 + 0.05x) and total (r = 0.71, P < 0.05; B, y = -0.29 + 0.96x) work production over 2 bouts of exercise. Values are given precreatine and postcreatine supplementation for 5 days (4 × 5 g/day). Numbers 1–8 refer to same subjects depicted in Fig. 2.
The initial bout of exercise resulted in a marked degradation of PCr (Table 1), but no significant difference was found when comparing treatments (49.1 ± 6.6 and 57.2 ± 3.1 mmol/kg dry matter pre- and post-Cr ingestion, respectively). Furthermore, no difference in PCr resynthesis during the recovery period was found pre- and post-Cr ingestion (88.1 ± 6.1 and 81.7 ± 3.7% of the preexercise resting value, respectively). No difference was found when comparing treatments (4.96 ± 2.9 and 47.4 ± 4.0 mmol/kg dry matter pre- and post-Cr ingestion, respectively). Furthermore, no difference in the increase in mixed-muscle TCr concentration, a large interindividual variation was observed in the change in resting PCr after Cr ingestion (type I fiber range 3.5-20.3 mmol/kg dry matter; type II fiber range -9.2 to 37.1 mmol/kg dry matter). There was also a suggestion that the PCr concentration before exercise bout 2 increased in type I (9.6 ± 4.3 mmol/kg dry matter) and type II (12.4 ± 7.4 mmol/kg dry matter) fibers after Cr ingestion (Table 2), but a large variation was found between subjects (type I fibers -5.6 to 24.2 mmol/kg dry matter; type II fibers -9.2 to 37.8 mmol/kg dry matter).

Degradation of PCr in type I and type II fibers is shown pre- and post-Cr ingestion in Fig. 5. After Cr ingestion, mean PCr degradation in type I fibers remained unchanged during exercise bout 1 but was greater during exercise bout 2 (P < 0.05). Similarly, mean PCr degradation in type II fibers was not affected by Cr ingestion during exercise bout 1 but was greater during exercise bout 2 (P < 0.05).

The increase in PCr concentration before exercise bouts 1 and 2 in type II fibers, after Cr supplementation, was positively correlated with both an increase in PCr degradation during exercise in this fiber type (r = 0.78, P < 0.01) and with the increase in total work production (r = 0.66, P < 0.05). No corresponding correlations were found between the change in PCr concentration before exercise bouts 1 and 2 in type I fibers, after Cr supplementation, and changes in either PCr degradation during exercise (r = 0.22) or total work production (r = 0.32).

**DISCUSSION**

Dietary Cr supplementation has previously been shown to increase the rate of PCr resynthesis during recovery from maximal-intensity exercise in individuals who demonstrated close to or more than a 20 mmol/kg dry matter increase in muscle TCr concentration; in contrast, PCr resynthesis appeared to be unaffected by Cr supplementation in those individuals who demonstrated less than a 10 mmol/kg dry matter increase in muscle TCr. Therefore, whereas Cr supplementation evidently improved PCr resynthesis during recovery, it was clear from these results that the degree of improvement was critically dependent on the magnitude of the net accumulation of Cr in the muscle over the course of supplementation. In agreement with these findings, the results of the present experiment demonstrated that, although all subjects appeared to benefit from an improvement in exercise performance after Cr ingestion, the degree of improvement was clearly related to the magnitude of Cr accumulation in
Table 2. PCR concentration measured in type I and type II muscle fibers immediately before and after 2 bouts of 30-s maximal-intensity isokinetic cycling exercise

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Pre-Cr Ingestion</th>
<th>Post-Cr Ingestion</th>
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<tbody>
<tr>
<td>I</td>
<td>66.6 ± 4.2</td>
<td>18.7 ± 2.9*</td>
</tr>
<tr>
<td>II</td>
<td>79.3 ± 1.5</td>
<td>15.8 ± 5.0*</td>
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Values are means ± SE in mmol/kg dry matter. Each bout of exercise was performed at 80 revolutions/min and was separated by 4 min of recovery. Values are given precreatine and postcreatine supplementation for 5 days (4 X 5 g/day). * Significant differences pre- and postexercise (P < 0.05). † Significant differences between corresponding concentrations pre- and post-Cr ingestion (P < 0.05).

The muscle. This association is illustrated by Fig. 3, which shows that changes in both peak work production (r = 0.71, P < 0.05; Fig. 3A) and total work production (r = 0.71, P < 0.05; Fig. 3B) were related to the change in muscle TCr concentration and that the magnitude of the increase in muscle TCr concentration required to produce improvements in exercise performance was of the same order as that previously shown to facilitate PCR resynthesis (11).

Clearly, these data point to the importance of maximizing the increase in muscle TCr concentration when attempting to increase exercise performance via Cr supplementation. Previously published results (11, 16) indicate that the muscle TCr concentration before supplementation is an important determinant of subsequent increases in muscle TCr concentration during Cr ingestion. However, the present results demonstrate that the initial TCr concentration is not the sole determinant. Subjects 2 and 3 depicted in Fig. 2, for example, had the same initial TCr concentration; however, subject 2, for no obviously apparent reason, experienced a sixfold greater increase in muscle TCr concentration during supplementation. Given that animal studies have demonstrated both dietary and hormonal effects on Cr bioynthesis and muscle Cr uptake and retention (28), future work aimed at maximizing muscle Cr uptake during supplementation might focus on elucidating the principle factors regulating uptake in humans.

The present study extends previously published work that has also demonstrated that Cr supplementation can improve performance during maximal-intensity exercise (1, 5, 8, 12, 17), by performing a direct investigation of the effects of Cr supplementation on skeletal muscle energy metabolism. The 30% reduction in mixed-muscle ATP loss found during exercise in the present study, together with the observed increase in total work production, suggests that ADP rephosphorylation to ATP during exercise was improved as a consequence of Cr supplementation. This hypothesis is supported by previous studies in which an improvement in exercise performance after Cr ingestion was accompanied by a reduction in plasma ammonia (5, 12) and hypoxanthine (1) accumulation during exercise, since both of these metabolites are accepted markers of muscle adenine nucleotide loss during maximal-intensity exercise (15).

However, the factor(s) underlying the increase in exercise performance and concomitant reduction in ATP loss is not readily apparent from the mixed-muscle metabolite data of the present experiment. After Cr supplementation, the change in resting mixed-muscle PCR concentration ranged from -3.2 to 26.9 mmol/kg dry matter. Given that the rate of ATP resynthesis from PCR over the course of 30 s of maximal-intensity exercise is likely to be in the region of 1.5 mmol·kg dry matter·s⁻¹ (20), the larger increases in resting PCR concentration within this range may have made a significant contribution to total ATP production during exercise. However, no correlation was found between the change in mixed-muscle PCR concentration after Cr ingestion and subsequent changes in either mixed-muscle ATP loss, exercise performance, or muscle TCr concentration.

This finding is attributable to the observation that subjects with the greatest increase in muscle TCr concentration also showed the greatest increase in total
work production, i.e., the ATP requirement was higher, and the subsequent reduction in ATP loss observed during exercise was therefore proportionally lower.

One explanation for these findings may be that favorable metabolic effects arising from Cr supplementation were confined principally to one muscle fiber type, making the metabolic responses recorded in mixed muscle more difficult to interpret. Evidence is available showing that, although the resting PCr concentration of type II fibers is ~12% greater than that of type I fibers (13, 25, 26, 27), the rate of PCr degradation during 30 s of maximal-intensity dynamic exercise is 10–25% greater in type II muscle fibers (13, 27). Furthermore, the rate of PCr degradation was found to be 33% greater in type II compared with type I fibers during 20 s of high-intensity electrically evoked isometric contraction. During the final 10 s of contraction, a 60% fall in the rate of type II fiber PCr degradation was observed, whereas the rate of PCr degradation was reduced by 15% in type I fibers (25). Accordingly, the authors attributed the decline in muscle force during contraction to a fall in energy provision from PCr in type II fibers. It is reasonable to suggest, therefore, that Cr supplementation might exert a greater effect on this fiber type during maximal-intensity exercise. The present finding that the change in type II fiber PCr concentration before exercise bouts 1 and 2 was positively correlated with both a change in PCr degradation during exercise in this fiber type \( (r = 0.78, P < 0.01) \) and with a change in total work production \( (r = 0.66, P < 0.05) \) suggests that the increase in type II fiber PCr availability resulting from Cr ingestion may indeed have been responsible for the improvements found in exercise performance. Further support for this suggestion is provided by the observation that the change in type I fiber PCr concentration after Cr ingestion was unrelated to changes in both type I fiber PCr degradation during exercise \( (r = 0.22) \) and total work production \( (r = 0.32) \).

These findings suggest that the increase in type II fiber PCr concentration resulting from Cr supplementation might account for the observed increase in exercise performance. However, the increase in PCr concentration is likely to reflect an overall increase in the fiber TCr concentration, which may itself be responsible for improvements in exercise performance by increasing mitochondrial ATP production in type II fibers during exercise and recovery. This suggestion is supported by studies showing that the increase in muscle TCr concentration after Cr supplementation was principally in the form of Cr (11, 16), which was in turn likely to be responsible for accelerating the rate of PCr resynthesis in human muscle during recovery from intense ischemic contraction (11). In vitro studies have demonstrated that Cr can increase the rate of respiration in skeletal muscle mitochondria (3) and skinned cardiac muscle fibers (9), and the role of Cr as an acceptor of mitochondrial ATP has been discussed in a series of papers (3, 4, 23, 29). The uptake of Cr by different muscle fiber types was not investigated in the present study. However, given that the TCr concentration of fast contracting skeletal muscle is 45% greater than that of slow muscle (10) and that the increase in PCr concentration was greater in type II fibers in the present study, it appears likely that Cr uptake was greater in this fiber type.

Peak work production during exercise bouts 1 and 2 occurred within 2 s of the onset of exercise in the present study, and a possible improvement in peak work production as a result of an increase in energy substrate availability seems unlikely. However, both an increase in peak power output during isokinetic cycling (5) and an increase in maximal strength (8) have been reported after Cr supplementation. The mechanism(s) responsible for these improvements in performance are unknown but may be related to the increase in body mass found after Cr supplementation by Balsom et al. (1) and Greenhaff et al. (11), which may be related in turn to an increase in fat-free mass (8). Whether these changes can explain the improvements seen in maximal work production and strength needs to be investigated.

In agreement with previous studies in which blood lactate production during maximal-intensity exercise was unchanged after Cr ingestion (5, 12), mixed-muscle lactate production during exercise appeared to be unaffected by Cr ingestion in the present study. However, a decrease in blood lactate accumulation has been observed during repeated bouts of maximal-intensity exercise lasting 6 s and separated by recovery periods of 30 s duration (1). One possible explanation for this discrepancy lies with the duration of exercise; the dephosphorylation of ADP to AMP during an exercise period of 6 s has the potential to be buffered by PCr to a greater extent than during maximal-intensity exercise lasting 30 s, since the PCr store of skeletal muscle has been shown to decrease by >50% within the first 10 s of maximal-intensity exercise (19). The accumulation of free AMP, a known allosteric activator of phosphorylase \( a \) (22) and thereby the rate of glycogenolysis, would therefore be proportionally lower, and more likely to be buffered effectively by the increase in PCr resulting from Cr supplementation, than would be the case during maximal-intensity exercise lasting 30 s. If so, then the lower lactate production found after Cr ingestion by Balsom et al. (1) may be attributable to improved buffering of ADP dephosphorylation, and thereby AMP accumulation, during successive bouts of exercise lasting 6 s.

In conclusion, the present study has demonstrated a positive relationship between increases in muscle TCr concentration and improvements in performance during maximal dynamic exercise. The results suggest that this ergogenic effect can be attributed to increased ATP resynthesis during exercise, as a consequence of increased PCr availability in type II muscle fibers.

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