Effects of creatine on isometric bench-press performance in resistance-trained humans

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1Centre for Exercise Science and Medicine, Institute of Biomedical and Life Sciences, University of Glasgow, Glasgow, UK; 2Sport and Exercise Science Research Centre, South Bank University, London, UK; 3School of Chemical and Life Sciences, University of Greenwich, London, UK; and 4Department of Physiotherapy, Podiatry and Radiography, Glasgow Caledonian University, Glasgow, Scotland, UNITED KINGDOM

ABSTRACT

KILDUFF, L. P., P. VIDAKOVIC, G. COONEY, R. TWYCROSS-LEWIS, P. AMUNA, M. PARKER, L. PAUL, and Y. P. PITSILADIS. Effects of creatine on isometric bench-press performance in resistance-trained men. Med. Sci. Sports Exerc., Vol. 34, No. 7, pp. 1176–1183, 2002. Purpose: The purpose of this study was to investigate the effects of creatine (Cr) supplementation on force generation during an isometric bench-press in resistance-trained men. Methods: 32 resistance-trained men were matched for peak isometric force and assigned in double-blind fashion to either a Cr or placebo group. Subjects performed an isometric bench-press test involving five maximal isometric contractions before and after 5 d of Cr (20 g·d−1 Cr + 180 g·d−1 dextrose) or placebo (200 g·d−1 dextrose). Body composition was measured before and after supplementation. Subjects completed 24-h urine collections throughout the study period; these were subsequently analyzed to provide total Cr and creatinine excretion. Results: The amount of Cr retained over the supplementation period was 45 ± 18 g (mean ± SD), with an estimated intramuscular Cr storage of 43 (13–61) mmol·kg−1 dry weight muscle (median [range]). Four subjects in the Cr group were classified as “nonresponders” (≤21 mmol·kg−1·dry weight muscle increase following Cr supplementation) and the remaining 17 subjects were classed as “responders” (≥32 mmol·kg−1·dry weight muscle). For the Cr group, peak force and total force pre- or post-supplementation were not different from placebo. However, when the analysis was confined to the responders, both the change in peak force [Repetition 2: 59(81) N vs -26(85) N; Repetition 3: 45(59) N vs -26(64) N] and the change in total force [Repetition 1: 1471(1274) N vs 209(1517) N; Repetition 2: 1575(1254) N vs 196(1413) N; Repetition 3: 1278(1245) N vs -3(1118) N; Repetition 4: 918(935) N vs -83(1095) N] post-supplementation were significantly greater compared with the placebo group (P < 0.01). For the Cr group, estimated Cr uptake was inversely correlated with training status (r = −0.68, N = 21, P = 0.001). Cr significantly increased body weight (84.1 ± 8.6 kg pre- vs 85.3 ± 8.3 kg post-supplementation) and fat-free mass (71.8 ± 6.0 kg pre- vs 72.6 ± 6.0 kg post-supplementation), with the magnitude of increase being significantly greater in the responder group than in the placebo group. Conclusion: Five days of Cr supplementation increased body weight and fat-free body mass in resistance-trained men who were classified as responders. Peak force and total force during a repeated maximal isometric bench-press test were also significantly greater in the responders compared to the placebo group. Key Words: ORAL CREATINE MONOHYDRATE, PEAK FORCE, TOTAL FORCE, BODY COMPOSITION, RESISTANCE-TRAINED SUBJECTS

The energy required to perform brief explosive-type exercise is almost exclusively provided by the high-energy phosphate stores in skeletal muscle. As the phosphocreatine (PCr) stores become depleted, performance rapidly deteriorates, reflecting the inability to resynthesize phosphocreatine from creatine. The ability to resynthesize PCr stores becomes depleted, performance rapidly deteriorates, reflecting the inability to resynthesize phosphocreatine from creatine. The ability to resynthesize PCr stores becomes depleted, performance rapidly deteriorates, reflecting the inability to resynthesize phosphocreatine from creatine.
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Training adopted by resistance-trained subjects, and also

isotonic), it partly simulates the

press maneuver (i.e., the test is isometric, while the training

bench-press test is unable to replicate the typical bench-

maximal performance using an isometric bench-press test in

performance of isometric exercise. The

tical investigation has been given to the effects of Cr

sprint performance (5,10) and promote greater gains in

(1,13,16), increase fat-free mass (2,18), improve anaerobic

that oral Cr loading can increase muscle Cr content

ment on performance of isometric exercise. The

aim of the present study was therefore to determine the

effects of Cr supplementation on strength endurance and

maximal performance using an isometric bench-press test in

ia. Although the isometric bench-press test is unable to replicate the typical bench-

 maneuver (i.e., the test is isometric, while the training

or competitive maneuver is isotonic), it partly simulates the

training adopted by resistance-trained subjects, and also

allows force to be measured with a high degree of accuracy.

### METHODS

#### Subjects

Thirty-two healthy resistance-trained men (Table 1), from whom written informed consent had been obtained, volunteered to take part in the study which was approved by the local ethics committee. The experimental procedures were in accordance with the policy statement of the American College of Sports Medicine. Subject eligibility was initially assessed by interview. No subject had a history of cardiovascular or respiratory disease and/or evidence of musculoskeletal injury. Subjects were recruited on the basis that they were engaged in a structured weight-training program at the time of recruitment. All subjects had at least 2 yr training experience and were demonstrated not to have supplemented with Cr for at least 8 wk before the study. Investigators did not reveal before interview that subjects would be excluded if they had supplemented with Cr in the last 8 wk. Eight subjects (four in each group) had previously supplemented with Cr. No Cr was detected in the baseline urine samples of any subject. Subjects typically undertook 3 to 4 resistive-training sessions per week, with an emphasis on major muscle groups. All subjects completed at least one heavy dynamic bench-press session per week (e.g., two warm-up sets at ~ 50% of the subject’s one repetition maximum (1RM), pyramiding up to 1RM within 4 sets).

#### Experimental design

Before entering the experimental phase of the study, subjects visited the laboratory on at least two occasions in order to become familiar with the isometric bench-press and related protocols. Familiarization trials were carried out until the variability of two consecutive performances was within 100 N for peak force. The test-retest reliability of the isometric bench-press revealed a high intra-class correlation (ICC) for both performance outcomes (Peak force ICC = 0.95, Total force ICC = 0.95; these test-retest reliability values are based on subjects having each undergone three familiarization tests). On the basis of the final familiarization results (peak force), subjects were assigned in a double-blind fashion to either a Cr group or a placebo group on a 2/1 ratio; this asymmetry was designed to accommodate both responders and nonresponders to Cr supplementation (11). Following the

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### TABLE 1. Physical characteristics of the two groups of subjects.

<table>
<thead>
<tr>
<th></th>
<th>Placebo Group (N = 11)</th>
<th>Creatine Group (N = 21)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>24 ± 5</td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179 ± 8</td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>80.1 ± 7.3</td>
<td>80.2 ± 7.1</td>
</tr>
<tr>
<td>Total body water (L)</td>
<td>48.4 ± 3.7</td>
<td>48.5 ± 3.9</td>
</tr>
<tr>
<td>Total body water (%)</td>
<td>60.0 ± 3.6</td>
<td>60.6 ± 2.8</td>
</tr>
<tr>
<td>Lean body mass (kg)</td>
<td>69.3 ± 5.6</td>
<td>69.4 ± 5.8</td>
</tr>
<tr>
<td>Lean body mass (%)</td>
<td>86.7 ± 4.1</td>
<td>86.7 ± 4.1</td>
</tr>
<tr>
<td>Body fat (kg)</td>
<td>10.9 ± 3.8</td>
<td>10.8 ± 3.7</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>13.4 ± 4.1</td>
<td>13.3 ± 4.1</td>
</tr>
<tr>
<td>Peak power (N)</td>
<td>815 ± 255</td>
<td></td>
</tr>
<tr>
<td>Training history (yr)</td>
<td>5 ± 2</td>
<td></td>
</tr>
</tbody>
</table>

Values are mean ± SD.
familiarization period, all subjects performed two isometric bench-press tests at least 5 d apart. The first isometric bench-press test was conducted 48 h after the subject’s final familiarization trial. The supplementation period for both groups started on the day after the first isometric bench-press test and finished the day before the second one. The experimental design is shown in Figure 1.

The Cr group ingested 22.8 g · d⁻¹ Cr · H₂O (equivalent to 10 g Cr × 2 daily) for 5 d before and after each daily training session. Each pre- and post-workout supplement dose consisted of 11.4 g of Cr · H₂O (equivalent to 10 g Cr) and 90 g of glucose polymer made up in 500 mL of warm to hot water. This regimen was adopted in light of the work by Harris et al. (13) who found that this protocol increased resting muscle PCR levels within 5 d. A number of studies have used a 5-d Cr supplementation period in trained individuals and found ergogenic effects (22,23). Dissolving Cr in warm to hot water prevented any detectable formation of creatinine (Crn), with no parts of the supplement remaining undissolved. The addition of dextrose to the Cr has been shown to significantly enhance the uptake of Cr (10,24). On training days, subjects consumed the first Cr dose 1 h before exercise and the second Cr dose immediately postexercise. On nontraining days, subjects took the supplement ad libitum. The placebo group consumed 202.8 g · d⁻¹ of glucose polymer (101.4 g × 2 daily) for 5 d, prepared and administered in an identical fashion to the Cr supplement. Both supplements had similar taste, texture, and appearance and were placed in generic packets to ensure double-blind administration.

Subjects were instructed to follow their normal diet (apart from the extra carbohydrate [CHO] contained in the experimental drinks) and to weigh and record all food and drink consumed. Digital weighing scales readable to 1 g were used. The diet was analyzed for energy intake and macronutrient content using a computerized version of McCance and Widdowson’s food composition tables (14). Subjects were also requested to eliminate caffeine and caffeine-containing foods from their diet to minimize the possible inhibitory effects of caffeine on the ergogenic effect of Cr (28). Throughout the duration of the study subjects were encouraged to maintain their normal training habits. At the end of the study, all subjects gave verbal assurance that they had complied with these instructions. Subjects completed seven separate 24-h urine collections. The first was started on the day preceding supplementation (baseline), then continued through the 5 d of supplementation, and finished on the day following supplementation. The urine was collected over a 24-h period in a 5 L container provided by the investigators. The volume of urine collected for each 24-h period was measured and mixed thoroughly, with a representative 20 mL sample being stored at −20°C for subsequent analysis (ABX Mira Plus Spectrophotometer, ABX Diagnostics, Bedfordshire, UK) of Cr and Crn concentrations using a spectrophotometric enzymatic Crn Kit (MPR1-Kit no. 839434, Roche Diagnostics Ltd., East Sussex, United Kingdom). Total Cr excretion was corrected for the mean increase in Crn following supplementation.

Procedures. Subjects reported to the laboratory on the morning of testing after a standardized meal and having refrained from alcohol intake, caffeine intake, and strenuous exercise the day before. Following the measurement of height and body mass, percentage body fat, fat free mass, and total body (TBW) water were measured (Bodystat-1500 Bioimpedance analyzer, Bodystat Ltd., Isle of Man) using a standard bioimpedance technique (19,29). The measurements were taken while the subjects lay comfortably in a supine position on a nonconductive surface, with their arms and legs slightly abducted. Before the start of the isometric bench-press test, all subjects underwent a standardized warm-up consisting of 5 min of arm cranking at 25 W, followed by a series of stretches with an emphasis on stretching the musculature associated with the bench-press maneuver.

Each subject then performed five consecutive maximal isometric bench-presses. A padded bench was positioned over a calibrated force platform (Kistler type 9281B, Kistler Instruments Corporation, Winterthur, Switzerland) so that the force platform was directly under the subject’s shoulders. A weight stand of adjustable height was positioned on either side of the bench, and a 1 m bar was laid across the stands and permanently fixed in this position. Subjects were required to position themselves on the bench with their elbows at 90° flexion and with their hands positioned no more than 81 cm apart. Each subject was asked to assume a comfortable pressing position on the bench. The subject’s head, hand, and the stand height positions were noted, and the subject was required to reproduce the same position on each testing occasion. For each isometric bench-press, subjects were given a 5 s count-down and told to press against the bar as hard as possible for 20 s, a duration that has been shown to deplete PCR stores by ~98% (27). The force exerted against the bar was transmitted by the bench to the force platform in the vertical plane, and the peak, total force (area under the curve) and fatigue index (the percent decline in force production within each 20-s period) for each bench-press was calculated using the Kistler software provided (Kistler BioWare, Version 2.22, Kistler Instruments Corporation). This maneuver was repeated four more times, with 2 min recovery periods. The recovery period was adopted in light of the findings by Greenhaff et al. (11) of increased rate of PCR rephosphorylation during the second min of recovery from intense muscular contractions following Cr supplementation. Subjects adopted the “ready” position in the last minute of each recovery period. All post-supplementation testing was carried out at the same time of day and in the same manner. Consumption of water (500 mL) was permitted during each bench-press test. Room temperature was maintained between 20 and 24°C.

Data analysis. Data were expressed as the mean ± SD or median (range), following a test for the normality of distribution. Statistical analysis was carried out using two factor ANOVA for repeated measures, followed by paired t-test, or two-sample t-test, as appropriate. Statistical significance was declared at P < 0.05.
RESULTS

Diet. During the study period, the daily diet of the Cr group comprised 13.4 ± 2.5 MJ·d⁻¹, of which 59 ± 6%, 27 ± 6%, 14 ± 4%, and 0 ± 0% of energy intake was in the form of CHO, fat, protein, and alcohol, respectively. The daily diet of the placebo group comprised 13.3 ± 1.7 MJ·d⁻¹, of which 59 ± 5%, 25 ± 6%, 14 ± 4%, and 2 ± 3% of energy intake was in the form of CHO, fat, protein, and alcohol, respectively. There was no difference in energy intake or dietary composition between groups.

Urinary analyses. In the placebo group, Crn excretion over the 6 d was not different from baseline. In the Cr group, Crn excretion increased from 1.6 ± 0.4 g·day⁻¹ on the first day to 4.0 ± 1.1 g·day⁻¹ on the final day of supplementation. Daily Cr excretion was therefore corrected for Crn excretion. Urinary Cr excretion also increased during the supplementation period in the Cr group. Estimated Cr uptake was greatest on the first day of supplementation (15 [7–20] g) and was lowest on the final day of supplementation (7 [4–15] g) (median [range]). The estimated Cr uptake was calculated by subtracting the total Cr excreted (corrected for Crn excretion) from the total amount supplemented per day. Of the 20 g of Cr administered each day, 75 (33–100)% was retained on the first day of supplementation and 34 (−18–77)% on the last day of supplementation. The total amount of Cr retained over the supplementation period was 45 ± 18 g of the total supplemented dose (i.e., 100 g), with an estimated increase in intramuscular Cr concentration of 43 (13–61) mmol·kg⁻¹ dry weight muscle (based on an estimated muscle mass of 40% of body mass and an average muscle water of 77% of wet weight, Bergstrom et al. (3).). In the placebo group, no Cr was detected in the urine during the study. Out of the 21 subjects in the Cr group, 4 subjects were classified as nonresponders (≤21 mmol·kg⁻¹·day dry muscle weight increase following Cr supplementation) and the remaining 17 subjects were classed as responders (≥32 mmol·kg⁻¹·day dry weight muscle). The estimated Cr uptake for the responders group was 51 (32–61) mmol·kg⁻¹·day dry weight muscle compared to an estimated Cr uptake of 14 (13–21) mmol·kg⁻¹·day dry weight muscle for the nonresponders. These two distinct groups are evidence of an “ergogenic threshold”. These estimated Cr uptakes are very similar to those measured by Greenhaff et al. (11). In that study, the nonresponders had a Cr uptake of about 10 mmol·kg⁻¹·day dry weight muscle, and all but one of the responders had a Cr uptake greater than 25 mmol·kg⁻¹·day dry weight muscle. Similarly, in the present study all but one nonresponder had a Cr uptake of about 13 mmol·kg⁻¹·day dry weight muscle, and all responders had a Cr uptake above 30 mmol·kg⁻¹·day dry weight muscle.

Physical characteristics. The physical characteristics of the two groups of subjects were similar before supplementation (Table 1). In the Cr group, body weight increased significantly from 84.1 ± 8.2 kg to 85.3 ± 8.3 kg following supplementation (P < 0.001), with no change in the placebo group (80.1 ± 7.3 kg to 80.2 ± 7.1 kg, P = 0.76). The magnitude of change in body weight was significantly greater in the Cr group compared with the placebo group (P = 0.003). Absolute and percentage body fat and TBW were not different between groups; however, there was a significant increase in body weight in the responders over time (49.9 ± 4.3 L to 50.6 ± 4.9 L, P = 0.019).

As with the Cr group as a whole, there was a significant increase in body weight in the responders to Cr following supplementation (84.1 ± 8.6 kg to 85.3 ± 8.3 kg, P = 0.000). The gain in body weight over the supplementation period was also significantly greater (P < 0.01) in the responders compared with the placebo group (Figure 2). The change in FFM over the supplementation period was significantly greater (P = 0.038) in the responders compared with the placebo group (Figure 2). Body weight for the nonresponders did not increase following Cr supplementation (84.2 ± 7.9 kg to 84.2 ± 7.4 kg, P = 0.94). The gain in body weight was thus significantly greater (P = 0.017) in the responders compared with the nonresponders. There was no significant increase in average body fat for the responders or placebo group post-supplementation (i.e. 12.2 ± 3.9 kg to 12.6 ± 3.8 kg, P = 0.237 and 10.9 ± 3.8 kg to 10.8 ± 3.7 kg, P = 0.788, respectively). Figure 2 shows less than 0.3 kg nonsignificant increase in body fat for the responder group and a nonsignificant decrease in body fat of 0.3 kg in the placebo group; both are within day to day measurement variation.

Isometric bench-press performance. Peak force and total force were not significantly different between the Cr and placebo groups before supplementation. In both groups, there was a significant decrease in peak force over the five repetitions during both the pre-supplementation and post-supplementation bench-press tests. There was a nonsignificant tendency for the magnitude of change (i.e., post-supplementation minus pre-supplementation) in peak force and total force to be significantly greater in the Cr group compared with the placebo group (P = 0.054 and P = 0.078, respectively). However, when this analysis was repeated after removing the nonresponders from the Cr group, the magnitude of change in peak force and total force was significantly greater in the responders compared with the placebo group (P = 0.003 and P = 0.000) (Figure 3). The
percent decline in force production within each 20-s period (fatigue index) for each bench-press was not significantly different when comparing the pre- with the post-supplementation values in either group, or after excluding the nonresponders from the Cr group.

**Correlations.** A significant negative correlation was found between estimated Cr uptake and training experience in the Cr group ($r = -0.68, N = 21, P = 0.001$) (Figure 4A). Subjects in both the Cr group and the placebo group had, on average, $5 \pm 2$ yr heavy resistance training experience ($P = 0.22$). Estimated Cr uptake was also positively correlated with the change in body weight over the supplementation period ($r = 0.55, N = 21, P < 0.01$) (Figure 4B). Estimated Cr uptake was significantly correlated with the change (pre- to post-) in total force for the first four repetitions (Repetition 1: $r = 0.53, P = 0.013$; Repetition 2: $r = 0.47, P = 0.033$; Repetition 3: $r = 0.44, P = 0.044$; Repetition 4: $r = 0.49, P = 0.026$). There was also a significant positive correlation between the magnitude of change in total force over the five repetitions (total change in force for each repetition added together) and estimated Cr uptake ($r = 0.508, N = 21, P = 0.019$) (Figure 4C). No significant association was found when protein intake was correlated against estimated Cr uptake ($P = 0.79$).

**Side effects.** In general, subjects tolerated the supplementation protocol well with no reports of gastrointestinal distress or muscle cramping. Three subjects (i.e., two subjects in the Cr group and one subject in the placebo group) reported experiencing mild headaches, possibly due to the high glucose concentration of the ingested supplements.

**DISCUSSION**

In the present study, 5 d of Cr supplementation significantly increased peak isometric force and total force during repeated 20 s isometric bench-press exercise in a group of 17 responders compared with the placebo group (Figure 3). As muscle biopsies were not obtained in this study, one can only speculate on the potential mechanisms for this improvement in performance following Cr supplementation. Nevertheless, increased PCr availability and PCr resynthesis during recovery from maximal exercise of this type are the most plausible, as muscle fatigue has previously been associated with a depletion of muscle PCr stores (15,27). Cr supplementation has the potential to increase the basal levels of PCr and, by doing so, to delay the onset of muscle...
A number of previous studies support this view (1,11).

Since the seminal work of Harris et al. (13) and Greenhaff et al. (11), many investigators have tested the hypothesis that strength, power and/or work performed during repeated sets of maximal dynamic contractions can be improved by increasing total muscle Cr concentration by Cr ingestion. However, not all studies have reported an ergogenic effect. Of the 45 pertinent papers published to date (to our knowledge, and not including abstracts), 33 have demonstrated an ergogenic effect. It is interesting to note that Greenhaff et al. (11) found a substantial increase in total muscle Cr concentration only in subjects with a presupplementation total muscle Cr concentration of the order of 120 mmol·kg⁻¹-dry muscle weight or less, and that these same individuals demonstrated an accelerated rate of PCR resynthesis during the second min of recovery from intense electrically-evoked contractions of the vastus lateralis.

Greenhaff et al. (11) and Casey et al. (5) subsequently showed an ergogenic effect of Cr supplementation when the post-supplementation increase in intramuscular [Cr] exceeded 20 mmol·kg⁻¹-dry muscle weight. For example, Casey et al. (5) reported that Cr supplementation produced a 23.1 ± 4.7 mmol·kg⁻¹-dry muscle weight increase in [Cr] and an increase in peak and total work produced during two bouts of 30 s maximal isokinetic cycling. Similarly, Maganaris and Maughan (21) showed that Cr supplementation (10 g Cr·d⁻¹ for 5 d) increased the estimated muscle [Cr] by about 30 mmol·kg⁻¹-dry muscle weight and increased isometric force generating capacity and isometric endurance. In contrast, however, Snow et al. (23) found only a small increase in muscle [Cr] following 30 g of Cr·d⁻¹ for 5 d (i.e., 11.7 ± 2.4 mmol·kg⁻¹-dry muscle weight) and no significant improvement in sprint-exercise performance. A similar outcome was reported more recently by Finn et al. (7) for 4 by 20 s all-out sprint performance in 8 endurance trained cyclists following 5 d of Cr supplementation. They too found only a small increase in muscle [Cr] (16.2 mmol·kg⁻¹-dry muscle weight), with three out of the eight subjects increasing [Cr] by less than 10 mmol·kg⁻¹-dry muscle weight. It should be pointed out that these authors could be making a type II error (25) consequent to both the small sample size and the low Cr retention that was particularly marked in three of their eight subjects.

These several observations emphasize the importance of recognizing that substantial individual differences can occur in intramuscular Cr uptake following Cr supplementation. The classification of subjects into responders and nonresponders (5,11) is suggestive of what might be termed an ergogenic threshold for Cr uptake of about 20 mmol·kg⁻¹-dry muscle weight, as proposed by Greenhaff et al. (11) and Casey et al. (5). Greenhaff showed an increased rate of PCR resynthesis during recovery following Cr ingestion in subjects whose muscle Cr concentration increased by on average 20 mmol·kg⁻¹-dry muscle weight, but conversely subjects whose muscle Cr concentration increased by <10 mmol·kg⁻¹-dry muscle weight following Cr supplementation showed very little or even a slower rate of PCR resynthesis during recovery. Our findings provide support for this contention. Only when the four nonresponders (in whom the increase in intramuscular [Cr] was estimated to be ≤21 mmol·kg⁻¹-dry muscle weight) were excluded from the Cr group did the improved isometric bench-press performance clearly emerge, in terms of both peak force and total force. Furthermore, the finding of a significant correlation between estimated Cr uptake and delta total force in repetitions 1 through 4 would suggest that subjects with the greatest Cr uptake had the greatest performance benefit, and this is in agreement with previous published work (5). While these findings provide evidence consistent with an ergogenic threshold, assigning a specific threshold value is not possible, as Cr uptake was only estimated in the present study. Nevertheless, these estimated Cr uptake values are very similar to those measured by Greenhaff et al. (11).

One explanation for the two distinct groups (i.e. responders and nonresponders) with regard to Cr uptake may be the varying amount of intramuscular Cr before supplementation. This might reflect, for example, a low habitual dietary intake of Cr in the responders and/or conversely, a high dietary intake of Cr in the nonresponders. Whether this was the case in these particular subjects cannot be established. While our subjects carried out a weighed intake of food, it was not possible to estimate meaningfully the dietary Cr content, as the amount of Cr in each item of food is dependent on many factors including food preparation. Even so, one might reasonably expect that subjects with a high protein intake might also have a high Cr intake. However, we found no significant correlation between protein intake and estimated Cr uptake (P = 0.79). Also, protein intake was not different in the responders and nonresponders.

Another possible explanation could be the strength-training status of our subjects. MacDougall et al. (20) have reported that only 5 months of heavy resistance training can increase resting muscle [Cr] by 39% and [PCr] by 22%. Our subjects had 5 ± 2 yr of heavy resistance training experience, which could predispose them to high resting levels of intramuscular Cr and PCr. Variability in training status may therefore be another factor responsible for the conflicting results reported in the literature. Interestingly, a significant negative correlation was found between training experience and estimated Cr uptake (Figure 4). This is an area that we feel needs further investigation.

Although other studies have found no significant difference in body mass after short-term Cr supplementation (20 to 30 g·d⁻¹ for 5 to 7 d) (12,24,26), the majority of studies have produced increases ranging from 0.6 to 1.8 kg after short-term Cr supplementation (6,10,11,21,26). Considering the short time course of this increase in body weight, some investigators have attributed these increases to increases in TBW. For example, Hultman et al. (16) found a 0.6 L decline in urinary volume after acute Cr supplementation (20 g·d⁻¹ for 6 d), and therefore attributed the increase in body weight to Cr-stimulated water retention. These authors also noted that the time course of urinary volume changes paralleled that of muscle Cr uptake. Furthermore, an increase in both total body and intracellular water was
demonstrated by Ziegenfuss et al. (31) with acute Cr ingestion (0.35 g·kg⁻¹·fat free mass·d⁻¹ for 3 d), with the increase in TBW accounting for approximately 90% of the acute gain in body mass. It remains to be determined whether this increase in water is associated with an increase in protein synthesis. The balance of available evidence from human performance studies using Cr supplementation and more direct evidence from animal in vivo and in vitro experiments would support the notion that increasing Cr availability may indeed increase protein synthesis (8,17,18). In the present study, supplementation with Cr increased body weight (84.1 ± 8.6 kg pre-supplementation to 85.3 ± 8.3 kg post-supplementation), with the mean increase in the responder group (1.2 ± 0.9 kg) being significantly greater (P < 0.01) than that of the placebo group (0.1 ± 0.6 kg) (Figure 2). The increase in body weight cannot be explained by the increases in TBW alone as a result of Cr stimulated water retention, as there was no significant increase in TBW expressed as percentage of body weight. Despite a significant increase in TBW in absolute terms in the Cr group (49.9 ± 4.3 L to 50.6 ± 4.9 L, P = 0.019), if the relative volume of TBW remains constant (as in the present study), the gain in body mass may not be attributed to water retention. The increase in absolute TBW seen in this study after Cr supplementation may be indicative of intracellular water that normally accompanies dry matter growth. Francaux and Poortmans (8) found similar results and interpreted their findings in the same manner. Cr supplementation also promoted significantly greater gains in FFM in the responder group compared with the placebo group (P = 0.038). Alternatively, the increase in absolute TBW following Cr supplementation could be indicative of an increase in body fat along with water retention. Resolution of this issue requires additional research using more precise and invasive methods.

**CONCLUSION**

The results of this study suggest that 20 g Cr·d⁻¹ for 5 d did not result in a significant increase in peak force or total work during repeated isometric contractions in resistance-trained individuals. However, this was due to the nonresponders in the Cr group masking the effects of the remaining group. When the Cr group was considered with only responders to Cr in the group, Cr supplementation resulted in significant increases in peak force and total force.

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**REFERENCES**


20. MacDougall, J. D., G. R. Ward, D. G. Sale, and J. R. Sutton. Biochemical adaptation of human skeletal muscle to heavy resis-


