

Review article

CREATINE SUPPLEMENTATION AND SWIM PERFORMANCE: A BRIEF REVIEW

Melissa J. Hopwood¹✉, Kenneth Graham² and Kieron B. Rooney¹

¹School of Exercise and Sport Science, Faculty of Health Sciences, Sydney University, Australia.

²New South Wales Institute of Sport, Australia.

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ABSTRACT

Nutritional supplements are popular among athletes participating in a wide variety of sports. Creatine is one of the most commonly used dietary supplements, as it has been shown to be beneficial in improving performance during repeated bouts of high-intensity anaerobic activity. This review examines the specific effects of creatine supplementation on swimming performance, and considers the effects of creatine supplementation on various measures of power development in this population. Research performed on the effect of creatine supplementation on swimming performance indicates that whilst creatine supplementation is ineffective in improving performance during a single sprint swim, dietary creatine supplementation may benefit repeated interval swim set performance. Considering the relationship between sprint swimming performance and measurements of power, the effect of creatine supplementation on power development in swimmers has also been examined. When measured on a swim bench ergometer, power development does show some improvement following a creatine supplementation regime. How this improvement in power output transfers to performance in the pool is uncertain. Although some evidence exists to suggest a gender effect on the performance improvements seen in swimmers following creatine supplementation, the majority of research indicates that male and female swimmers respond equally to supplementation. A major limitation to previous research is the lack of consideration given to the possible stroke dependant effect of creatine supplementation on swimming performance. The majority of the research conducted to date has involved examination of the freestyle swimming stroke only. The potential for performance improvements in the breaststroke and butterfly swimming strokes is discussed, with regards to the biomechanical differences and differences in efficiency between these strokes and freestyle.

KEY WORDS: Phosphocreatine, breaststroke, butterfly, ergometer, power, gender.

INTRODUCTION

Creatine (Cr) is an amino acid synthesized primarily in the liver and stored mostly in the muscle. The phosphorylated form, phosphocreatine (PCr) plays an integral role in anaerobic energy production in the muscle. PCr is directly involved in the formation of adenosine tri-phosphate (ATP) via the creatine kinase reaction:



Normal endogenous levels of PCr will be sufficient to maintain ATP production for the initial 5-10 seconds of high intensity, explosive exercise. The supply of PCr is limited, and its depletion is considered to be a major contributor to fatigue during such activity (Dawson et al., 1995; Greenhaff et al., 1993; Harris et al., 1992).

Exogenous creatine supplementation can be used to increase intramuscular Cr and PCr stores. Commonly, total muscle Cr stores have been shown to increase by 20-30% following five days of

supplementation at a dose of 20g per day (Harris et al., 1992). Following this acute loading period, a maintenance dose of 2-5g creatine per day for a further 22-28 days is recommended to sustain elevated intramuscular Cr levels, and hence any improvements in performance that may have been obtained (Terjung et al., 2000; Vandenberghe et al., 1997; Volek et al., 1999). However, it must be noted, that despite increases in muscle Cr and PCr stores following a five day creatine loading period, by the end of a six week maintenance period of 2g creatine per day, muscle Cr and PCr stores have been observed to decline and return to baseline levels (van Loon et al., 2003).

Creatine supplementation at the above mentioned dosage appears to have no short or long term adverse health effects (Mihic et al., 2000; Peeters et al., 1999; Schilling et al., 2001; Volek et al., 1999). However, an increase in body weight is commonly associated with creatine supplementation (Balsom et al., 1993a; 1993b; 1995; Greenhaff et al., 1994; Kirksey et al., 1999; Kreider et al., 1998; Mihic et al., 2000; Stone et al., 1999; Vandenberghe et al., 1997; Volek et al., 1999), and there is some anecdotal evidence of increased incidence of gastrointestinal discomfort and muscle cramps following supplementation (Peeters et al., 1999; Schilling et al., 2001).

A number of studies have looked at the effects of creatine supplementation on exercise performance. The greatest improvements in performance following creatine supplementation have been observed during repeated bouts of high intensity exercise. Measurements of power during multiple bouts of maximal cycling efforts (Balsom et al., 1993a; Birch et al., 1994; Dawson et al., 1995; Kreider et al., 1998), torque production during a series of repeated maximal voluntary contractions (Greenhaff et al., 1993; Vandenberghe et al., 1997), and the time taken to complete repeated middle distance runs (Harris et al., 1993) have all been shown to improve following creatine supplementation.

Proposed mechanisms for such improvements include increased availability of PCr for ATP synthesis during contraction (Balsom et al., 1993a; Birch et al., 1994; Greenhaff et al., 1993; Harris et al., 1993; Greenhaff et al., 1994; Dawson et al., 1995; Terjung et al., 2000), increased availability of free Cr for PCr resynthesis during recovery (Balsom et al., 1993a; Greenhaff et al., 1993; 1994; Dawson et al., 1995), and an improved muscle buffering capacity (Greenhaff et al., 1993; Harris et al., 1992; Terjung et al., 2000). Creatine supplementation also appears to enhance the beneficial effects of resistance training on muscle strength (Kreider et al., 1998; Peeters et al., 1999; Rawson and Volek, 2003;

Stone et al., 1999; Vandenberghe et al., 1997; Volek et al., 1999).

Whilst creatine supplementation may be beneficial in improving repeated bursts of high intensity anaerobic activity, research indicates that single sprint efforts are not likely to be enhanced by creatine supplementation (Dawson et al., 1995; Odland et al., 1997; Snow et al., 1998). Despite some evidence to suggest that creatine supplementation may benefit aerobic endurance exercise (Engelhardt et al., 1998), the majority of research indicates that this type of exercise is not enhanced following creatine supplementation (Balsom et al., 1993b; Stroud et al., 1994, Vandebuerie et al., 1998).

Although several studies examining the effects of creatine supplementation have been performed on athletes (Harris et al., 1993; Kirksey et al., 1999; Kreider et al., 1998; Stone et al., 1999), much of the existing research has been conducted in the laboratory or the gymnasium. To date, very little evidence exists to suggest that the benefits obtained following creatine supplementation transfer through to the sporting field and competition situations (Mujika and Padilla, 1997). It is therefore necessary to consider the effects of creatine supplementation on performance in a variety of competitive sports both in training and competition situations.

This review examines the specific effects of creatine supplementation on swimming performance. The review also considers the effects of creatine supplementation on various measures of power development in swimmers. The Medline and Sport Discus databases were searched using a combination of the keywords "creatine" and "swim". All articles examining the effects of creatine supplementation on either single sprint swim performance and/or repeated interval swim set performance were retrieved. It appears generally, that whilst creatine supplementation does not reduce the time to complete a single sprint swim, repeated interval swim set performance may be improved with creatine supplementation.

CREATINE SUPPLEMENTATION AND SWIMMING PERFORMANCE

The anaerobic energy contribution to swimming performance can be as high as 80% for a 50 meter sprint (Holmer, 1983; Toussaint and Hollander, 1994). Therefore, considering the potential benefits of creatine supplementation on anaerobic exercise performance [Reviewed in (Terjung et al., 2000)], it would be reasonable to expect that swimming performance could improve following creatine supplementation. However, support of a beneficial effect of creatine supplementation on swimming

performance in the literature is inconsistent. Ambiguity in the literature can be attributed to variations in study design such as the performance outcomes measured; the exercise protocol examined; the supplementation protocol followed; the size of the pool used for testing; and the training status of the swimmers. Furthermore, a definitive statement concerning the efficacy of creatine supplementation and performance enhancement in swimming is not easily acceptable given the variation in the age and gender of the study populations examined (See Tables 1 and 2). However, evidence does exist to suggest that like previously reported cycling (Balsom et al., 1993a; 1995; Birch et al., 1994; Kreider et al., 1998) and running studies (Harris et al., 1993), creatine supplementation may improve repeated swim performance.

CREATINE SUPPLEMENTATION AND SINGLE SPRINT SWIMMING PERFORMANCE

As mentioned previously, creatine supplementation has little to no effect on improving single sprint performance in exercise modes such as cycling and running (Dawson et al., 1995; Odland et al., 1997; Snow et al., 1998). As can be seen in Table 1, current literature agrees that it is unlikely creatine supplementation would be of benefit to single sprint performance in swimming. Utilizing a variety of different supplementation regimes, research shows that the time to complete a single sprint swim does not improve following creatine supplementation (Burke et al., 1996; Mujika et al., 1996; Peyrebrune et al., 1998; Thompson et al., 1996; Dawson et al., 2002). In fact, Mujika and colleagues (1996) observed a slight reduction in performance following creatine supplementation. The authors suggested this was possibly due to altered swimming mechanics and changed fluid dynamics as a result of an increase in body weight following creatine supplementation.

The result of a null effect of creatine supplementation on single sprint swimming performance is not surprising considering that a single sprint would produce a less marked depletion in PCr stores compared to a repeated sprint effort. Consequently, the relationship between elevated muscle PCr stores following creatine supplementation and the prevention of a performance reduction is weakened during single sprints compared to repeated sprints.

More specifically, several reasons behind the null effect of creatine supplementation on single sprint swimming performance relate to the associated increases in intramuscular Cr stores following each individual supplementation regime.

With the exception of Thompson et al. (1996), no other studies examining the effect of creatine supplementation on single sprint swimming performance directly measured intramuscular Cr or PCr levels. Since such measurements were not taken, it is difficult to assess the effectiveness of creatine supplementation on increasing Cr stores in this population.

A common supplementation regime that has been shown to significantly elevate intramuscular Cr levels involves ingesting 20-30g creatine per day for five to seven days (Greenhaff et al., 1994; Harris et al., 1992; Snow et al., 1998; Terjung et al., 2000; Vandenberghe et al., 1997; Volek et al., 1999). The studies of Burke et al. (1996), Mujika et al. (1996), and Dawson et al. (2002) utilized this same supplementation regime in their examination of single sprint swimming performance. Considering this, it would be reasonable to assume that in these studies, intramuscular Cr stores were elevated following supplementation. Therefore, it is unlikely that the lack of improvements seen in the aforementioned studies can be attributed to an insufficient elevation of intramuscular Cr stores. Thompson et al. (1996) did measure PCr concentrations in the muscle, however no changes were found following the supplementation period. The authors attribute this to negative feedback, such that exogenous creatine supplementation actually suppresses the endogenous biosynthesis of Cr, resulting in no changes to the combined concentration of Cr and PCr in the muscle. Consequently, any effect that might have been expected following supplementation could have been counteracted. Alternatively, the dose of creatine administered to the subjects (2g creatine per day) was relatively low when compared to other studies, and may not have been sufficient to induce an elevation in total muscle Cr levels.

Harris et al. (1992) and Greenhaff et al. (1994) indicate that the extent of Cr uptake into the muscle is inversely related to an individual's initial muscle Cr content. The higher the initial intramuscular Cr concentration, the more difficult it is to increase stores (Greenhaff et al., 1994; Harris et al., 1992). In addition, it is reported that there is an upper limit to the amount of Cr that can be stored in the muscle (Terjung et al., 2000). It is therefore speculated that the subjects involved in these studies could have had a relatively high intramuscular Cr content to begin with, and so additional creatine ingestion was not beneficial.

Burke et al. (1996) suggest the possibility that muscle PCr levels are not a limiting factor in the performance of a single sprint swim lasting between 25 and 100 meters. This, however, is difficult to accept considering the ATP-PCr energy system is

Table 1. The effect of creatine supplementation on single sprint swimming performance.

	Subjects	Supplementation Protocol	Test Protocol	Results	
				Performance	Body Composition
Burke et al. 1996	32 (18 Male; 14 Female) 17-25 yrs National level swimmers	5g Creatine monohydrate + 2g sucrose OR 5g polyglucose + 2g sucrose 4 x per day, 5 Days Randomised, double blinded	Preferred stroke 1x25m sprint 1x50m sprint 1x100m sprint 10mins active recovery + 2-3mins passive recovery between sprints	No significant performance changes in any of the trials in either group	Not specified
Havenetidis et al. 1996	21 (11 Male; 10 Female) Elite swimmers	2 identical supplementation periods; 4 months apart 5g Creatine OR 5g placebo 5 x per day, 4 Days No randomisation, double blinded	Stroke not specified Official meet race performance Distance not specified	Significant improvement in race time (2.1%) following first supplementation period for the creatine group only Further improvements in race times (3.0%) following second supplementation period for the creatine group only	Not specified
Mujika et al. 1996	20 (11 Male; 9 Female) ~ 20 yrs National or international level swimmers	5g Creatine monohydrate OR 5g lactose placebo 4 x per day, 5 Days Randomisation not specified, double blinded	Preferred stroke 1x25m sprint 1x50m sprint 1x100m sprint 300m active recovery + 20-25 mins passive recovery between sprints	No significant performance changes in any of the 3 trials or the sum of the 3 trials in either group Tendency towards reduced performance in 25m and 50m swims in the creatine group	Significant increase in body weight (1%) in the creatine group only
Thompson et al. 1996	10 (Female) University swimmers	2g Creatine OR 2g placebo 1 x per day, 6 Weeks Randomised, blinding not specified	Freestyle 1x100m sprint 1x400m sprint	No significant effect on swim time in either sprint for either group	No change to lean body mass
Peyrebrune et al. 1998	14 (Male) ~ 20-21 yrs National level swimmers	3g Creatine + 1.5g maltodextrin + 1.5g glucose OR 6g glucose 3 x per day, 5 Days Randomised, double blinded	Preferred stroke 1x50yd sprint	No effect on performance in either group	Not specified
Dawson et al. 2002	20 (10 Male; 10 Female) ~ 16 yrs	Acute loading period: 5g creatine monohydrate + 1g glucose polymer OR 6g glucose polymer	Freestyle 1x50m sprint 1x100m sprint	No significant improvements in performance for either group	No significant body mass changes Skinfold totals

	Competitive swimmers	4 x per day; 5 days Maintenance period: 5g creatine monohydrate OR 5g glucose polymer; 1 x per day; 22 days Randomised, single blinded	3x100m recovery swims on a departure interval of 1.5 mins		decreased for both groups, but were not statistically different from the respective baseline scores
Selsby et al. 2003	15 (8 Male; 7 Female) ~ 19 yrs Division III collegiate swimmers	Acute loading period: 0.3g creatine / kg body weight OR varying doses of dextrose placebo 5 x per day, 5 days Maintenance period: 2.25g creatine OR varying doses of dextrose 1 x per day, 9 days Randomised, double blinded	Freestyle 1x50yd sprint 1x100yd sprint	Trend towards improved performance in both sprints in the creatine group Trend towards reduced performance in both sprints in the placebo group	No significant weight gain within groups
Mendes et al. 2004	18 (12 Male; 6 Female) ~ 19 yrs Competitive Swimmers	5g Creatine + 20g CHO OR 20g CHO 4 x per day, 8 Days Double blind, placebo controlled	1 x 50m sprint 1 x 100m sprint	No effect on performance in either group	Significant increase in total body mass, lean body mass and body water in the creatine group only No change in bone or muscle mass

responsible for 80% of energy production during a 50 meter swim, and 25% of energy production during a 100 meter swim (Costill et al., 1992). Additionally, Peyrebrune et al. (1998) argue that the rate of the creatine kinase reaction responsible for ATP production is partly determined by PCr concentration. At the beginning of exercise, PCr levels will be high, and so the rate of this reaction will be close to maximum. Consequently, to increase PCr concentration beyond normal levels will not affect the rate of the reaction, and therefore short term (sprint) swimming performance will be unaffected. If this is the case however, artificially increasing intramuscular PCr levels will allow the creatine kinase reaction to continue at a high rate for a longer period of time, and hence, may actually be of benefit to longer sprints.

The lack of effect of creatine supplementation on single sprint swimming performance could relate to the magnitude of the changes in performance observed following supplementation. Burke et al. (1996) and Dawson et al. (2002) suggest that the changes in swim performance that occur as a result of creatine supplementation are smaller than the normal intra-swimmer variance

during sprint performance, hence leading to insignificant results. Dawson et al. (2002) further suggest that because the margins of improvement observed following creatine supplementation in swimmers are often very small, it is difficult to prove statistical significance despite a possible sporting significance of the results.

Mujika et al. (1996) propose a different mechanism for the null effect of creatine supplementation on single sprint swimming performance. Here, the authors suggest that the lack of improvement is caused by the increased body weight commonly associated with acute creatine loading. It is proposed that an increased body weight will alter the hydrostatic forces experienced between the swimmer and the water, hence altering stroke mechanics, increasing energy expenditure and counteracting any performance benefits that may have otherwise been induced by creatine supplementation. It should be noted however, that Theodorou et al. (2005) reported improvements in swimming performance despite a weight gain similar to that seen by Mujika et al. (1996).

Despite the evidence of a non-effect of creatine supplementation on single sprint swimming performance, a trend towards improved performance in single 50 yard and 100 yard sprints has been observed (Selsby et al., 2003). Although results did not reach significance, Selsby et al. (2003) demonstrated slight improvements in the performance of both a single 50 yard and a single 100 yard freestyle sprint in a creatine supplemented group, whilst a placebo control group showed a slight decrease in performance. The improvements seen are attributed by the authors to the performance level of the subjects examined. The subjects involved in this study varied in both ability and previous involvement in swimming. The authors suggested that lower level swimmers may have a greater capacity to increase their intramuscular stores of Cr than their elite counterparts, who may already have Cr levels at their physiological maximum. Whilst it is possible that the elite subjects had high initial muscle Cr content, hence limiting their capacity to elevate stores through supplementation, muscle Cr levels were not measured, so we can not be sure of this. It is commonly accepted that intramuscular total Cr stores do not increase in response to training (Burke et al., 2003; Dawson et al., 1998; Tesch et al., 1990; Volek et al., 1999), so it may be possible that the improvements in performance seen by Selsby et al. (2003) are due to some other physiological adaptation associated with an increased training load in sub elite athletes.

In addition to Selsby et al. (2003), Havenetidis et al. (1996) reported improved race performance following creatine supplementation. Whilst we can assume the findings of Havenetidis et al. (1996) also support a beneficial effect of creatine supplementation on single sprint swimming performance, neither the stroke performed nor the distance of the race are specified by the authors.

CREATINE SUPPLEMENTATION AND REPEATED INTERVAL SWIM SET PERFORMANCE

Although creatine supplementation appears to have no effect on improving single sprint performance, much evidence exists to support a beneficial effect of creatine supplementation on repeated exercise performance (Balsom et al., 1993a; Birch et al., 1994; Dawson et al., 1995; Greenhaff et al., 1993; Harris et al., 1993; Kreider et al., 1998; Vandenberghe et al., 1997). In a similar fashion to cycling and running, performance over a repeated interval swim set also appears to improve following creatine supplementation. Whilst Peyrebrune et al.

(1998) found no performance differences between a creatine supplemented group and a placebo control group during a single 50 yard sprint, in the same subject population, creatine supplementation did lead to a significant reduction in the time to perform an interval set of 8x50 yard sprints. Evidence of a beneficial effect of creatine supplementation on repeated swimming performance is also demonstrated by Havenetidis et al. (1996), Grindstaff et al. (1997), Theodorou and Cooke (1998), and Theodorou et al. (1999) (see Table 2).

Repeated interval swim set performance following acute creatine loading with or without carbohydrate has also been investigated (Mendes et al., 2004; Theodorou et al., 2005). Mendes et al. (2004) found no improvements in repeated interval performance following combined creatine and carbohydrate ingestion, however Theodorou et al. (2005) found that although combined creatine and carbohydrate ingestion did lead to performance improvements during a repeated interval swim set, these improvements were no greater than those achieved following supplementation with creatine alone (Theodorou et al., 2005). Mero et al. (2004) considered the effects of combined creatine and sodium bicarbonate supplementation on repeated interval swim set performance. Whilst there was no experimental group supplemented with creatine alone, the combination of creatine and sodium bicarbonate did lead to performance improvements over that of a placebo control group (Mero et al., 2004).

Considering that repeated short term exercise bouts stress the phosphocreatine energy system to a greater extent, and for a longer period of time than a single sprint effort (Green, 1997), it is not surprising to see improved repeated interval swim set performance following creatine supplementation. However, the mechanisms behind creatine having a beneficial effect on repeated interval swimming performance are uncertain. Peyrebrune et al. (1998) suggest that the mechanism for improved repeated interval swimming performance following creatine supplementation relates to altered creatine kinase kinetics. It is speculated that supplementation causes intramuscular Cr concentrations to be maintained above the Km point of the creatine kinase reaction. Such an elevation in muscle Cr levels has two major benefits. Firstly, the rate of PCr resynthesis between sprints will increase, resulting in increased levels of PCr available for the next sprint effort. Secondly, elevated intramuscular Cr concentrations may lead to an improved muscle buffering capacity. Since the process of ATP resynthesis from adenosine-diphosphate (ADP) and PCr consumes a hydrogen ion (H^+) (Greenhaff et al., 1993), the increased rate

Table 2. The effect of creatine supplementation on repeated interval swim set performance.

	Subjects	Supplementation Protocol	Test Protocol	Results	
				Performance	Body Composition
Havenetididis et al. 1996	21 (11 Male; 10 Female) Elite swimmers	2 identical supplementation periods; 4 months apart 5g Creatine OR 5g placebo 5 x per day, 4 Days No randomisation, double blinded	Stroke not specified 10x50m sprints at 1min intervals 8x100m sprints at 2min intervals 15x100m sprints at 1min 40sec intervals	Greater improvements in performance for the creatine group compared to the placebo group following the first supplementation period. Further improvements in performance following the second supplementation period for the creatine group.	Not specified
Grindstaff et al. 1997	18 (7 Male; 11 Female) ~ 15 yrs Regionally/nationally competitive amateur swimmers	21g Creatine monohydrate + 4.2g maltodextrin OR 25.2g maltodextrin 9 Days Randomised, double blinded	Freestyle 3x100m sprints 60sec passive rest between sprints	Swim 1 and 2: Improved performance for the creatine group oOnly. Swim 3: No changes in performance in either group Trend towards reduced cumulative sprint time in the creatine group.	No significant differences between groups in changes in total body mass and percent body water. Changes in fat free mass tended to be greater in the creatine group. Changes in fat mass and percent body fat tended to be lower in the creatine group.
Peyrebrune et al. 1998	14 (Male) ~ 20-21 yrs National level swimmers	3g Creatine + 1.5g maltodextrin + 1.5g glucose OR 6g glucose 3 x per day, 5 Days Randomised, double blinded	Preferred stroke 8x50yd sprints at 1min 30sec intervals	Significant reduction in cumulative swim time (2%) in the creatine group.	Not specified
Theodorou and Cooke 1998	12 (8 Males; 4 Females) ~ 17 yrs Elite Swimmers	Acute loading period: 5g creatine 5 x per day, 4 days Maintenance period: 5g creatine OR 5g placebo 1 x per day, 8 weeks Randomised, blinding not specified	Stroke not specified 10x50m sprints; 60sec - swim time recovery 8x100m sprints; 2min - swim time recovery	Significant improvements in mean swim time (2%) after acute Loading. No significant difference in mean swim time between post acute loading and the end of 2 months.	Not specified
Leenders et al. 1999	32 (18 Male; 14 Female) ~ 19 yrs Competitive university swimmers	Acute loading period: 4 x 5g creatine dissolved in 150ml 6% maltodextrin solution OR 150ml 6% maltodextrin solution 4 x per day, 6 days Maintenance period: 5g Creatine dissolved in	Preferred stroke 6x50m sprints at 3min intervals 10x25yd sprints at 60s	Significant improvement in velocity (2%) over 6x50m interval set in males only following creatine supplementation. No improvements in velocity over	No significant changes in body mass, fat free mass and percent body fat.

		150ml 6% maltodextrin solution OR 150ml maltodextrin solution 2 x per day, 7 days Randomised, double blinded	intervals	10x25y interval set in males or females following creatine supplementation.	
Theodorou et al. 1999	22 (12 Male; 10 Female) ~ 19 yrs National level swimmers	Acute loading period: 5g creatine monohydrate 5 x per day, 4 days Maintenance period: 5g creatine monohydrate OR 5g polythene glycol 4000 1 x per day, 8 weeks Randomised, blinding not specified	Stroke not specified 10x50m sprints; 60sec - swim time recovery 8x100m sprints; 2min - swim time recovery 15x100m sprints; 2min - swim time recovery	Significant improvements in mean swim time (1.5%) after acute Loading. No significant difference in mean swim time between post acute loading and the end of 2 months maintenance for either group.	Significant increase in body mass (0.6%) following acute creatine loading.
Mendes et al. 2004	18 (12 Male; 6 Female) ~ 19 yrs Competitive swimmers	5g Creatine + 20g CHO OR 20g CHO 4 x per day, 8 Days Double blind, placebo controlled	Preferred stroke 3 x 3 x 50m sprints 30 second intervals between sprints 150 second intervals between sets	No effect on performance in either Group.	Significant increase in total body mass, lean body mass and body water in the creatine group only. No change in bone or muscle mass.
Mero et al. 2004	16 (8 Male; 8 Female) ~ 17-18 yrs National level swimmers	5g Creatine OR 5g maltodextrin 4 x per day, 6 Days 0.3g Maltodextrin OR 0.3g Sodium Bicarbonate per kg of body weight on the test day	Freestyle 2 x 100m sprints 10 minutes passive rest between sprints	Increase in swim time between the 2 sprints was greater in the placebo group than the combination creatine and sodium bicarbonate group.	No significant changes in body weight or percent body fat.
Theodorou et al. 2005	10 (6 Male; 4 Female) ~ 17-18 yrs High performance swimmers	5g Creatine OR 5g creatine + 500ml glucose syrup 5 x per day, 4 Days Randomised, blinding not specified	Preferred stroke 10x50m sprints; 60sec - swim time recovery 8x100m sprints; 2min - swim time recovery	Significant improvements in swimming velocity for both groups (2% Cr only group; 0.7% Cr + CHO group) No significant difference in the magnitude of improvement between groups	Most swimmers gained weight. Mean weight gain was larger in the creatine + carbohydrate group than the creatine only group. Significant and positive correlation between increase in mean velocity and increase in mean body mass in creatine and carbohydrate group only.

of PCr turnover as a result of an increased intramuscular Cr concentration, will lead to the consumption of more hydrogen ions. This, therefore, could improve muscle buffering capacity and delay fatigue.

Grindstaff et al. (1997) suggest that a combination of an improved ability to tolerate training, an enhanced ability to maintain velocity during sprints, and a greater capacity to recover from the sprints is likely to be responsible for the improvements seen in repeated interval swim set performance following creatine supplementation. It appears that the physiological basis behind improved repeated interval swimming performance following creatine supplementation is not yet defined, with the majority of researchers uncertain as to why such an effect can be seen.

It is possible that the performance improvement apparent during the repeated sprint efforts may be the result of an interaction between oxidative metabolism and the PCr energy system. There is biochemical evidence (Walsh et al., 2001) to suggest that via metabolic compartmentalization of creatine kinase, the PCr-Cr pathway interacts with both aerobic and anaerobic metabolism (Havenetidis, 2005). Furthermore, repeated cycling sprints utilize a greater proportion of aerobic energy supply than individual sprints (Bogdanis et al., 1996). It is possible, that aerobic metabolism is enhanced with the use of repeated sprint protocols either in conjunction with (Havenetidis, 2005) or independently of (Burgomaster et al., 2005), creatine supplementation.

Although the evidence for a beneficial effect of creatine supplementation on repeated maximal efforts seems convincing, Leenders et al. (1999) show conflicting results. Leenders et al. (1999) found that following creatine supplementation, average velocity over a 10x25 yard repeated interval swim set was unchanged. It was proposed by the authors that this is likely to be due to the short recovery period between sprints being insufficient to allow PCr stores to be adequately replenished. Interestingly, in the same subjects, the effects of creatine supplementation on an interval set of 6x50 meters differed according to gender. Average velocity over the swim set improved for males following creatine supplementation, but the same supplementation regime failed to induce any such improvements in the female swimmers. This is suggestive of a gender effect in the response to creatine supplementation, which leads us to consider gender as a potential limitation to the effect of creatine supplementation on improving swim performance (see below).

CREATINE SUPPLEMENTATION AND POWER DEVELOPMENT IN SWIMMERS

Several of the studies conducted on creatine supplementation and swimming performance have also examined the relationship between creatine supplementation and power development. Measurements of power commonly used to determine the effect of creatine supplementation on power development include total work performed, mean power output, peak power output, and time to reach peak power output. Research shows that such measures of power are highly correlated with sprint swimming performance, with improvements in mean power output and total work performed resulting from a four week strength training program, transferring to significant reductions in the time to complete a single sprint swim (Sharp et al., 1982). It is therefore reasonable to consider changes in power production, as measured on a cycle or swim bench ergometer, as a relevant indicator of performance improvements in swimming following creatine supplementation.

An early study looking at power development in swimmers utilized a cycle ergometer test to determine work performed and peak power output (Burke et al., 1996), whereas the more recent studies have tested power output using a biokinetic swim bench (Dawson et al., 2002; Grindstaff et al., 1997). The swim bench is a land based ergometer which requires the subject to lie prone, with their arms outstretched to handles attached to an air-braked wheel via a rope pulley system. The subjects legs are strapped down and they perform their stroke as they would in the water. Continuous power output and total work are assessed via a computer linked to the wheel. Details of studies examining the effect of creatine supplementation on power development in swimmers can be seen in Table 3.

Tests of power development using the cycle ergometer show creatine supplementation to have no effect on power development in national level swimmers. Burke et al. (1996) saw no changes in work performed, peak power output, or time to reach peak power output on the cycle ergometer following creatine supplementation. It is possible that no effect was seen because the leg ergometer test used is not specific to swimming performance. The authors argue that the cycle ergometer test involves the use of an untrained muscle group for this population, and that the test conducted was of a duration that is shorter than even the fastest swim sprint.

When tested on a swim bench ergometer however, creatine supplementation does in fact appear to improve power development. Grindstaff et

Table 3. The effect of creatine supplementation on power development in swimmers.

	Subjects	Supplementation Protocol	Test Protocol	Results
Burke et al. 1996	32 (18 Male; 14 Female) 17-25 yrs National level swimmers	5g Creatine monohydrate + 2g sucrose OR 5g polyglucose + 2g sucrose 4 x per day, 5 Days Randomised, double blinded	Cycle ergometer 2 x 10sec maximal effort sprints 10mins rest between sprints	No differences in work performed, peak power, or time to peak power between trials or between groups.
Grindstaff et al. 1997	18 (7 Male; 11 Female) ~ 15 yrs Regionally / nationally competitive amateur swimmers	21g Creatine monohydrate + 4.2g maltodextrin OR 25.2g maltodextrin 9 Days Randomised, double blinded	Swim bench ergometer 3x20sec maximal effort sprints 60sec rest between sprints	Greater overall changes in work performed by the creatine group than the placebo group Significant improvements in work performed during sprint 1 only (7.8%) for the creatine group only. No differences in peak power output between trials or between groups.
Dawson et al. 2002	20 (10 Male; 10 Female) ~ 16 yrs Competitive swimmers	Acute loading period: 5g creatine monohydrate + 1g glucose polymer OR 6g glucose polymer 4 x per day, 5 days Maintenance period: 5g creatine monohydrate OR 5g glucose polymer 1 x per day, 22 days Randomised, single blinded	Swim bench ergometer 2x30sec maximal effort sprints 10mins rest between sprints	Significantly greater increases in total work performed in the creatine group (7.5%) compared to the placebo group (2.0%)

al. (1997) found that creatine supplementation led to greater improvements in total work performed over three maximal effort sprints on the swim bench than those demonstrated by a placebo control group. Peak power output was unaffected by creatine supplementation, but work performed and total power output during the first of three sprints was significantly greater following creatine supplementation. It should be noted that this effect dissipated in sprints two and three of the test, leading to insignificant differences in mean power responses when the three sprints are considered as a whole. The authors suggest two possible explanations for this dissipation. It could be that the ergogenic effect of creatine supplementation may only last for one initial sprint as opposed to a repeated interval set, however, considering the available evidence on the benefits of creatine supplementation on swimming performance, single sprints are generally unaffected by creatine supplementation (Burke et al., 1996; Dawson et al., 2002; Mujika et al., 1996; Peyrebrune et al., 1998; Thompson et al., 1996). Alternatively, a longer rest period of six minutes has been shown to provide a more efficient phosphate transfer potential (Havenetidis, 2005).

Therefore, the sixty second recovery interval used between sprints in the testing procedure could be too brief to facilitate adequate recovery of PCr stores, regardless of any increases in intramuscular PCr concentrations that may have been induced by the supplementation period.

The results of Grindstaff et al. (1997) are supported by Dawson et al. (2002), who also found that creatine supplementation led to significantly greater increases in anaerobic work output on a swim bench ergometer. Interestingly, the increases in work performed during the repeated interval swim set on the swim bench occurred without a concurrent improvement in single sprint swimming performance. These findings further support the notion that creatine supplementation is beneficial for improving performance during repeated bouts of high intensity exercise, but not during single sprint efforts.

LIMITATIONS TO PREVIOUS RESEARCH

Whilst research suggests that creatine supplementation may be beneficial to the

performance of a repeated interval swim set but not to a single sprint effort, there is much inconsistency and ambiguity in the literature. Several limitations exist to research on swimming performance in general. These include such factors as the length of the pool tests are conducted in (25 meters or 50 meters), the length of the sprints incorporated into the testing protocol (25 yards, 50 yards, 50 meters or 100 meters), the stage in the swimming season that testing is conducted in, and the effects of taper on performance during testing. With respect to the effects of creatine supplementation on swimming performance however, there are three specific limitations to current research.

In addition to the absence of a direct measurement of intramuscular Cr levels (as mentioned previously), two other limitations to study design are particularly apparent. These are the effect of gender on the response to creatine supplementation, and the effect of creatine supplementation on the various competitive swimming strokes. Further research into both of these areas is essential in order to investigate the full potential of creatine supplementation on improving swimming performance.

THE EFFECT OF GENDER ON RESPONSE TO CREATINE SUPPLEMENTATION

The effect of gender on an athlete's capacity to improve performance following creatine supplementation is an area of much discussion. It has been speculated that females have higher endogenous muscle Cr levels than males (Forsberg et al., 1991), and so may respond less favorably to exogenous creatine supplementation (Harris et al., 1992). In addition, during high intensity repeated exercise, the anaerobic contribution to work performed is 35% lower in females than males (Hill and Smith, 1993). Considering this, it could be hypothesized that there is less capacity for the performance of high intensity repeated exercise to improve following creatine supplementation in women than in men. Despite this however, the majority of the evidence suggests that gender is not a determining factor for whether or not creatine supplementation is successful in improving performance (Harris et al., 1992; Tarnopolsky, 2000; Tarnopolsky and MacLennan, 2000; Rawson and Volek, 2003; Vandenberghe et al., 1997).

With the exception of Leenders et al. (1999), research on creatine supplementation and repeated interval swim set performance indicates gender does not appear to have any effect on the magnitude of performance improvements observed following creatine supplementation (Burke et al., 1996;

Dawson et al., 2002; Grindstaff et al., 1997; Havenetidis et al., 1996; Mendes et al., 2004; Mujika et al., 1996; Selsby et al., 2003; Theodorou and Cooke, 1998; Theodorou et al., 1999). In the study of Leenders et al. (1999), velocity over a 6x50m repeated interval swim set was found to improve in males following creatine supplementation, but not in females. As the data available on the benefits of creatine supplementation on female athletes is somewhat limited, it is unknown if the lack of performance improvement seen in the female swimmers by Leenders et al. (1999) is due to a physiological mechanism such as that previously described by Hill and Smith (1993), or some other factor. More research needs to be conducted into the gender effects of creatine supplementation on exercise and elite sporting performance.

THE EFFECT OF CREATINE SUPPLEMENTATION ON THE VARIOUS COMPETITIVE SWIMMING STROKES

Another major limitation to research considering the effects of creatine supplementation on swimming performance is related to examination of the various competitive swimming strokes (freestyle, backstroke, breaststroke and butterfly). None of the studies conducted to date have considered the effect of swimming stroke on the magnitude of performance improvement following a creatine supplementation regime. Recognizing that swimmers often specialize in a particular stroke or race distance, several studies have allowed the subjects to perform the test protocols in their preferred stroke of freestyle, backstroke, breaststroke or butterfly (Burke et al., 1996, Leenders et al., 1999, Mendes et al., 2004). However, upon analysis of results, all swimmers have been pooled together regardless of the stroke performed during the testing procedures. Other studies have tested performance of the freestyle swimming stroke only (Dawson et al., 2002; Grindstaff et al., 1997; Selsby et al., 2003; Thompson et al., 1996). Considering the evidence available to suggest considerable differences in efficiency between the strokes, it is surprising that stroke comparisons have not yet been made with regard to the effect of creatine supplementation on swimming performance.

Costill et al. (1992) indicate that the biomechanical difference between breaststroke and all other competitive swimming strokes is greater than that between any other two strokes. As a consequence, breaststroke swimmers expend more energy accelerating their bodies with each stroke,

resulting in much greater energy demands than those required by freestyle. Despite freestyle and butterfly being biomechanically more alike than any other two competitive swimming strokes (Costill et al., 1992), butterfly is the second least energy efficient of the strokes, with energy expenditure during butterfly and breaststroke almost twice that of freestyle and backstroke (Holmer, 1983). It is proposed by Holmer (1972) and Toussaint and Hollander (1994) that this large difference in energy expenditure is the result of the marked accelerations and decelerations within the stroke cycle.

Considering the role of creatine supplementation in elevating intramuscular PCr stores, sustaining ATP production during muscle contraction, and increasing the rate of ATP resynthesis during recovery, it is likely that creatine supplementation could be of benefit to repeated interval swim set performance. As a result of the high energy demands of the butterfly and breaststroke competitive swimming styles, potentially, the benefits associated with creatine supplementation and swimming performance could be greater when swimming breaststroke or butterfly, compared to the commonly examined freestyle swimming stroke.

CONCLUSIONS

Creatine supplementation and swimming performance has not received the same intensive research attention as other sports such as cycling. There appears to be some distinct limitations to research such as the absence of direct measurement of muscle creatine levels, possible gender effects, and a tendency to focus on the freestyle swimming stroke. However, it would appear that there is a potential benefit of creatine supplementation on repeated interval swim set performance.

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AUTHORS BIOGRAPHY

Melissa J. HOPWOOD

Employment

Honors student - BAppSc (Exercise and Sport Science), University of Sydney, Australia

Degree

BAppSc(Ex&SpSc)

E-mail: melissa.hopwood@ausport.gov.au

Kenneth GRAHAM

Employment

Manager, Sport Science and Medicine, NSW Institute of Sport, Australia

Degrees

BSc, MAppSc

Research interests

Factors limiting performance in sport; Recovery and adaptation in high performance athletes.

E-mail: kenneth.graham@nswis.com.au

Kieron B. ROONEY

Employment

Lecturer, School of Exercise and Sport Science, University of Sydney, Australia

Degrees

BSc, PhD

Research interests

Creatine supplementation, insulin secretion and carbohydrate metabolism.

E-mail: K.Rooney@fhs.usyd.edu.au

✉ Melissa J. Hopwood

Faculty of Health Sciences, C42 - Cumberland Campus, East Street PO Box 170, Lidcombe NSW 1825, Australia.

KEY POINTS

- Creatine supplementation does not improve single sprint swimming performance.
- Creatine supplementation does improve repeated interval swim set performance.
- Creatine supplementation does improve power development in swimmers when measured on a swim bench ergometer.
- As a result of the high energy demands of the butterfly and breaststroke competitive swimming styles, potentially, the benefits associated with creatine supplementation and swimming performance could be greater when swimming butterfly or breaststroke, compared to the commonly examined freestyle swimming stroke.