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The effects of different doses of caffeine on endurance cycling time trial performance

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Abstract
This study investigated the effects of two different doses of caffeine on endurance cycle time trial performance in male athletes. Using a randomised, placebo-controlled, double-blind crossover study design, sixteen well-trained and familiarised male cyclists (Mean ± s: Age = 32.6 ± 8.3 years; Body mass = 78.5 ± 6.0 kg; Height = 180.9 ± 5.5 cm \(V_{O2\text{peak}} = 60.4 ± 4.1 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}\)) completed three experimental trials, following training and dietary standardisation. Participants ingested either a placebo, or 3 or 6 mg \(\text{kg}^{-1}\) body mass of caffeine 90 min prior to completing a set amount of work equivalent to 75% of peak sustainable power output for 60 min. Exercise performance was significantly (\(P < 0.05\)) improved with both caffeine treatments as compared to placebo (4.2% with 3 mg \(\text{kg}^{-1}\) body mass and 2.9% with 6 mg \(\text{kg}^{-1}\) body mass). The difference between the two caffeine doses was not statistically significant (\(P = 0.24\)). Caffeine ingestion at either dose resulted in significantly higher heart rate values than the placebo conditions (\(P < 0.05\)), but no statistically significant treatment effects in ratings of perceived exertion (RPE) were observed (\(P = 0.39\)). A caffeine dose of 3 mg \(\text{kg}^{-1}\) body mass appears to improve cycling performance in well-trained and familiarised athletes. Doubling the dose to 6 mg \(\text{kg}^{-1}\) body mass does not confer any additional improvements in performance.

Keywords: Athletes, dose-response relationship, glucose, exercise, endurance, methylxanthine

Introduction
The ergogenic potential of caffeine on endurance performance tasks lasting approximately 1 hr have been well documented and summarised in a number of recent reviews (Burke, 2008; Doherty & Smith, 2004; Ganio, Klaau, Casa, Armstrong, & Maresh, 2009). Caffeine has been shown to be ergogenic in studies using a wide variety of dosing protocols (Doherty & Smith, 2004; Ganio et al., 2009). The optimal dose of caffeine required to elicit maximal high intensity endurance performance under relevant conditions (i.e. using valid performance tasks and when fed) is of interest to many athletes.

Early dose-response studies (Graham & Spriet, 1995; Pasman, vanBaak, Jeukendrup, & deHaan, 1995) suggested a bolus dose of 3–6 mg \(\text{kg}^{-1}\) body mass of caffeine provided 1 hr prior to exercise was ideal to improve endurance performance of approximately one hour duration. Graham and Spriet (1995) found that both low and moderate (3 mg \(\text{kg}^{-1}\) and 6 mg \(\text{kg}^{-1}\) body mass) doses of caffeine resulted in similar enhancements in running time to exhaustion, however, a higher dose of caffeine (9 mg \(\text{kg}^{-1}\) body mass) did not have a significant impact on performance as compared to placebo, despite having the greatest effect on epinephrine and blood-borne metabolite levels (Graham & Spriet, 1995). Pasman et al. (1995) also demonstrated improvements in performance (cycling) compared to placebo with 5 mg \(\text{kg}^{-1}\) body mass of caffeine but no further improvements with 9 or 13 mg \(\text{kg}^{-1}\) body mass doses, respectively. In both of these studies however, less than 10 participants were used and time-to-exhaustion protocols were employed. Time-to-exhaustion protocols have been suggested to better serve as tests of exercise capacity rather than absolute performance (Burke, 2008) whereas protocols based on fixed end point tasks, or time-trials have greater ecological validity.
Caffeine’s ergogenic effects on 30–60 min cycling time trial performance may also be seen at substantially lower doses (i.e., ≤3 mg · kg⁻¹ · body mass) (Jenkins, Trilk, Singhal, O’Connor, & Cureton, 2008; Kovacs, Stegen, & Brouns, 1998). Kovacs and colleagues (1998) demonstrated improved one hour time trial cycling performance compared to placebo in 14 well trained and fed participants given a total of 2.1 mg · kg⁻¹ body mass of caffeine. Further enhancements were then observed with 3.2 mg · kg⁻¹. However 4.5 mg · kg⁻¹ body mass of caffeine provided no additional benefits over 3.2 mg · kg⁻¹ body mass. The caffeine ingestion protocol involved the caffeine being mixed within a carbohydrate-electrolyte solution which was consumed prior to and throughout the exercise task (Kovacs et al., 1998).

More recently a dose-response study by Jenkins et al., (2008) observed no significant performance benefits when 1 mg · kg⁻¹ body mass of caffeine was given to 13 fasted participants one hour before a 30 minute cycling exercise task (15 min @ 80% \( V\text{O}_2 \pm 15 \) min time trial). However, when participants were provided with slightly higher caffeine doses (i.e., 2 and 3 mg · kg⁻¹ body mass) a similar performance improvement was observed (4% and 3% improvement, respectively) (Jenkins et al., 2008).

Taken together, these two studies suggest that caffeine is ergogenic in a dose-dependent manner up to 3 mg · kg⁻¹ body mass, with no additional gains in performance from doses >3 mg · kg⁻¹ body mass. Both of these studies however, neglected to include a higher caffeine dose for comparison delivered as a bolus prior to exercise consistent with the earlier dose-response studies employing the time-to-fatigue protocols. Hence it is therefore difficult to determine an optimal pre-exercise caffeine dose under sports specific conditions without using a higher dose for comparison.

Thus the purpose of this investigation was to determine the effects of two clearly contrasting pre-exercise bolus doses of caffeine on the performance of a 1 hr cycle time trial in well-trained and fed athletes. It was hypothesised that caffeine would improve endurance performance, compared with a placebo, but that there would be no greater benefits gained with the use of higher doses.

**Methods**

The study was carried out with approval from the Human Research Ethics Committee of Griffith University, Queensland, Australia.

**Participants**

Sixteen well-trained male cyclists (Mean ± s: Age = 32.6 ± 8.3 years; Body mass = 78.5 ± 6.0 kg; Height = 180.9 ± 5.5 cm \( V\text{O}_2\text{peak} = 60.4 ± 4.1 \) ml · kg⁻¹ · min⁻¹) volunteered to participate in the study.

**Preliminary testing**

Participants attended the laboratory on three occasions prior to the experimental trials. The first visit included medical screening, a questionnaire regarding their habitual caffeine consumption (mean 210 ± 115 mg · d⁻¹, range 10–600 mg · d⁻¹), and an incremental exercise test to exhaustion on an electronically-braked cycle ergometer (Lode Excalibur Sport, Lode, Groningen, The Netherlands), to determine participants’ individual \( V\text{O}_2\text{peak} \) values (ml · kg⁻¹ · min⁻¹) and peak power outputs (Desbrow, Barrett, Minahan, Grant, & Leveritt, 2009). Two familiarisation sessions involving the full exercise protocol followed, in which a self-selected warm-up and individual linear factors were established.

**Standardisation of conditions**

Participants were asked to abstain from all dietary sources of caffeine, alcohol and strenuous exercise for the 24 hr preceding each experimental trial. Participants consumed a pre-packaged standardised diet (200 kJ · kg⁻¹ body mass, including 7.5 g · kg⁻¹ body mass of carbohydrate for the 24 hr preceding each experimental trial and compliance with the exercise and dietary controls was confirmed verbally on the morning of each trial prior to testing. A light pre-exercise meal (42 kJ · kg⁻¹ body mass, including 2 g · kg⁻¹ body mass of carbohydrate) was provided on the morning of the trials. Additionally participants ingested 3 ml · kg⁻¹ body mass of 6% carbohydrate-electrolyte beverage during the warm-up, as well as upon completion of 30% and 60% of the target amount of work. To avoid any influence of circadian variance, experimental trials were performed at the same time of the day (mornings), with a 7 day wash-out period between each session. Trials were conducted in the same laboratory, on the same ergometer, under stable environmental conditions (~19–20°C, ~55% relative humidity).

**Experimental trials**

Each participant completed three time trials, in random order, under double-blind conditions. Participants reported to the laboratory approximately 2 hr before trials and after consuming the pre-exercise
meal, a resting 5 ml blood sample was taken via forearm venipuncture for subsequent analysis of plasma caffeine. At 90 min prior to the trials, participants ingested four opaque capsules containing either pure anhydrous caffeine (equivalent to 3 mg · kg⁻¹ body mass of caffeine (low dose caffeine) or 6 mg · kg⁻¹ body mass of caffeine (high dose caffeine)) or the placebo treatment containing approximately 400 mg of Metamucil® (100% psyllium husk fibre). After resting in a thermo-neutral environment, each participant performed a standardised warm-up and immediately prior to the commencement of the time trial, another venous blood sample (5 ml) was collected.

The time trial was performed with the ergometers set in linear mode. The participants’ linear factors were determined on an individual basis (during familiarisation) depending on their peak power outputs and were initially chosen so that 75% peak power output could be achieved at ~100 rpm, which was the preferred cadence for most cyclists. Participants were required to perform a set amount of work as fast as possible. The target amount of work was calculated according to the formula:

\[ \text{Total work (J) = 0.75 \cdot Peak Power Output \cdot 3600} \]

The same researcher supervised each time trial and provided standardised feedback to each participant. Subjective ratings of perceived exertion (RPE) (Borg, 1982) and heart-rate (HR) values (Polar Electro, Kempele, Finland) were recorded at each 10% of the time trial. Participants were able to view their HR, cadence and power output for the first 10% of the time trial only. After completion of the first 10% the only information available to participants was elapsed work as a percentage of the final work. No gas exchange data or blood samples were collected during the time trial. A final blood sample (5 ml) was taken immediately post-exercise for the analysis of plasma caffeine.

Upon completion of all three trials, participants were asked to attempt to identify the order of treatment for the trials, and to judge which trial they perceived to be representative of their best performance.

Blood sampling, storage and analysis

Venous blood (5 ml) was sampled before supplementation and immediately prior to-, and post-exercise. Samples were kept in lithium heparin vacutainers, before being centrifuged at 4000 rpm for 10 min at 5°C. Plasma was then extracted and stored at −84°C until subsequent analysis.

The quantitative analysis of plasma caffeine was performed using an automated “reversed-phase” high-performance liquid chromatography system, with conditions adapted with subtle modifications from Koch, Tusscher, Kopple and Guchelaar (1999). The precise method has been previously described (Desbrow et al., 2009). Plasma glucose was determined in duplicate using a commercial glucose analysis kit according to the manufacturer’s specifications on an automated blood biochemistry analyser (Cobas Integra 400, Roche Diagnostics, Switzerland).

Data analysis

Statistically significant differences were accepted at the 5% level. All dependent measures were analysed using repeated measures ANOVA exploring dose and time interactions. Where significant main effects were observed pair-wise (Bonferroni) comparisons were conducted to identify the specific nature of the differences. In addition, inferential statistics based on 95% confidence limits, were used to assess the clinical utility and practical applicability of results (Hopkins, 2000). The magnitude of the smallest worthwhile change in time trial performance was assumed to be an improvement/decrement in time to complete the set amount of work by >1% (when trials performed under conditions of caffeine treatment are compared to those performed under placebo conditions), based on the coefficient of variation (CV) derived from Laursen, Shing and, Jenkins (2003) using familiarised participants. The magnitude of the effect of caffeine was expressed using Cohen-type effect sizes and interpreted using a modified, performance-based scale (Hopkins, 2000). All results are reported as means ± s.

Results

Standardisation procedures

Mean 24 hr pre-trial energy and carbohydrate intakes were 195.90 ± 18.47 kJ · kg⁻¹ body mass and 7.15 ± 0.70 g · kg⁻¹ body mass, respectively. Participants reported no alcohol or tobacco use in the 24 hr prior to each trial. No strenuous exercise was reportedly undertaken during the 18 hr period before each trial. All participants complied with the instructions regarding the consumption of the carbohydrate-electrolyte beverages during the trials (707 ± 54 ml), and all drinks were well-tolerated.

Plasma caffeine and glucose

All participants commenced trials without measurable plasma caffeine (Figure 1) indicating a period of acute caffeine-abstinence was achieved. The plasma concentrations of caffeine rose rapidly following caffeine ingestion and both doses resulted in plasma
caffeine levels significantly different from placebo. Mean plasma caffeine levels were significantly higher for the high dose caffeine treatment, compared to the low dose caffeine treatment prior to exercise (35.18 ± 16.50 μmol·L⁻¹ and 16.35 ± 7.57 μmol·L⁻¹ respectively; \(P < 0.05\)), and post-exercise (37.98 ± 15.90 μmol·L⁻¹ and 17.74 ± 6.04 μmol·L⁻¹ respectively; \(P < 0.05\)). Plasma glucose values are provided in Table I. Irrespective of the trial, mean plasma glucose levels fell within the pre-ingestion to pre-exercise period \(P < 0.05\) but returned to pre-ingestion levels at the completion of exercise. Caffeine dose did not influence plasma glucose responses except for an elevated plasma glucose measure in the high dose caffeine trial compared to placebo following exercise \(P < 0.05\).

**Time trial performance, RPE and HR**

The mean time trial times for the placebo, low dose caffeine and high dose caffeine trials were 3902 ± 340 s, 3738 ± 286 s and 3791 ± 281 s, indicating significant performance improvements in the caffeine containing trials (4.21% with low dose caffeine \(P < 0.05\) and 2.84% with high dose caffeine \(P < 0.05\)). The mean difference between the low dose caffeine and high dose caffeine trials was not statistically significant \(P = 0.24\) (Table II). Twelve of 16 (75%) participants produced their slowest time trial performance on placebo with the remaining four participants producing their slowest time trial on high dose caffeine trials. Nine of the participants (56%) produced their best performance on low dose caffeine whereas five (31%) produced their best time on the high dose caffeine trial.

Caffeine ingestion at either dose resulted in significantly higher mean HR values as compared to placebo conditions \(P < 0.05\), but there was no significant difference in mean HR between the two caffeine trials \(P = 0.34\). No statistically significant differences in RPE values between any of the treatment conditions at any time point were noted \(P = 0.39\).

**Post trial investigations**

Six of the 16 participants (38%) correctly identified the treatment order of all three trials and five participants (31%) could distinguish when they had received the placebo treatment, but were unable to differentiate between the two caffeine trials. The majority (\(n = 12\), 75%) believed that they performed better when caffeine was ingested and more than half (\(n = 9\), 56%) of the participants correctly identified their fastest time trial.

**Discussion**

The purpose of this investigation was to determine the effects of two contrasting pre-exercise bolus doses of caffeine on the performance of a one hour cycle time trial. The results of this study indicate that caffeine is ergogenic to endurance cycling performance, with statistically significant enhancements in time trial times of 4.2% for low dose caffeine and 2.9% for high dose caffeine when compared to placebo. The magnitude of the effects demonstrated in this study appear to be consistent with data from previous studies using cycle time trials of 30–60 min duration which have demonstrated performance improvements ranging between 1.8–5.8% (Jenkins et al., 2008; Kovacs et al., 1998; McNaughton et al., 2008).

Two previous studies suggested that caffeine was ergogenic in a dose-dependent manner up to 3 mg·kg⁻¹ body mass, with no additional gains in performance from doses > 3 mg·kg⁻¹ body mass (Jenkins et al., 2008; Kovacs et al., 1998). However, the highest dose ingested within these studies was 4.5 mg·kg⁻¹ body mass of caffeine administered prior
Different doses of caffeine on cycling performance

Table II. Results of time trial following ingestion of 0, 3 and 6 mg·kg\(^{-1}\) body mass of caffeine.

<table>
<thead>
<tr>
<th>Treatment Comparison</th>
<th>Mean improvement (s) ± s 95% Confidence Limits</th>
<th>Cohen’s Effect Size</th>
<th>Qualitative outcome (P(<em>{\text{beneficial}}/P</em>{\text{trivial}}/P_{\text{harmful}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDC-PLA</td>
<td>164.3 ± 64.1a (55.2 to 273.5)</td>
<td>0.51</td>
<td>Almost certainly beneficial (100/0/0)</td>
</tr>
<tr>
<td>HDC-PLA</td>
<td>110.8 ± 83.5a (1.6 to 219.9)</td>
<td>0.35</td>
<td>Probably beneficial (92/7/0)</td>
</tr>
<tr>
<td>LDC-HDC</td>
<td>−53.6 ± 77.4 (−162.7 to 55.59)</td>
<td>0.17</td>
<td>Possibly harmful (3/53/63)</td>
</tr>
</tbody>
</table>

Time trial values are means ± s. Placebo (PLA) = 0 mg·kg\(^{-1}\) body mass, Low Dose Caffeine (LDC) = 3 mg·kg\(^{-1}\) body mass of caffeine, High Dose Caffeine (HDC) = 6 mg·kg\(^{-1}\) body mass of caffeine. *denotes significant differences compared to PLA.

to and throughout the performance task. The results of the present study provide further support that a moderate pre-exercise caffeine dose (3 mg·kg\(^{-1}\) body mass) is equally effective as a higher caffeine dose (6 mg·kg\(^{-1}\) body mass) at improving performance in fed and familiarised athletes.

The present findings are also consistent with earlier research using “time to fatigue” type protocols in that the higher doses of caffeine (>6–9 mg·kg\(^{-1}\) body mass) were associated with no additional performance improvements (Graham & Spriet, 1995; Pasman et al., 1995). Indicating that caffeine’s ergogenic potential exists in tests designed to reflect measures of exercise performance. Therefore we now have greater confidence that the optimal ergogenic dose is ~3 mg·kg\(^{-1}\) body mass for this type of exercise task.

Given that plasma caffeine increases proportionate to the dose administered, the current results and those of the recent meta-analysis (Conger, Warren, Hardy, & Millard-Stafford, 2011) indicate that the ergogenic potential of caffeine is unlikely to be related to higher levels of plasma caffeine in circulation. Indeed, Cox et al. (2002) initially demonstrated that small amounts of caffeine ingested in the form of a cola beverage had the potential to enhance cycling time trial performance despite eliciting only a very small increase in plasma caffeine. Given that higher caffeine doses are also more likely to result in adverse side-effects (Nawrot et al., 2003), clearly lower doses of caffeine have greater practical application for tasks of this duration.

Whilst many studies have demonstrated ergogenic effects associated with caffeine ingestion the possibility of known placebo effects associated with caffeine ingestion (Beedie, Stuart, Coleman, & Foad, 2006) must also be considered within the current study. Although the treatments were administered in a double-blind manner, the majority of participants (11/16) correctly identified the placebo trials at the conclusion of the study. Hence there is the potential that the participant’s awareness of an “active” intervention may have influenced subsequent performance. Nevertheless the performance improvement of 4.2% in the low dose caffeine treatment is somewhat greater than the magnitude of previously documented placebo effects (Beedie et al., 2006).

The current proposed ergogenic mechanisms of caffeine can be categorised by possible interrelated effects along two major themes i) central effects mediated via adenosine receptor antagonism, and ii) direct effects on skeletal muscle via influence on muscle electrolyte homeostasis (primarily Ca\(^{2+}\) and K\(^{+}\)) (Tarnopolsky, 2010). Given the protocol in the current study was selected to reflect competition environments (a self-paced time trial), the ability to elucidate further on possible ergogenic mechanisms is limited. As anticipated, HR values increased following caffeine ingestion in accordance with observations from other studies (Bridge & Jones, 2006; Cole et al., 1996). Additionally the RPE data confirmed that participants appear able to exercise at higher absolute intensities for a given rate of exertion supporting the theory that alteration in neural perception of effort may be one mechanism by which caffeine exerts its ergogenic effects (Doherty & Smith, 2005). Irrespective of the mechanism(s) involved the results of the present study confirm that high levels of plasma caffeine are not required to trigger the ergogenic responses within this type of exercise task.

Conclusion
The results of the study demonstrate that caffeine at either 3 or 6 mg·kg\(^{-1}\) body mass is beneficial to 1 hr cycling time trial performance. However greater levels of circulating caffeine resulting from the higher dose do not equate to better performance outcomes.

Practical application
Athletes planning to use caffeine for events of ~1 hr duration are best advised to use a moderate
pre-exercise caffeine dose (∼3 mg · kg$^{-1}$ body mass) to maximise the ergogenic potential whilst minimising possible side-effects.

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References


