The Effect of Adding Caffeine to Postexercise Carbohydrate Feeding on Subsequent High-Intensity Interval-Running Capacity Compared With Carbohydrate Alone

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The aim of this study was to test the hypothesis that adding caffeine to postexercise carbohydrate (CHO) feedings improves subsequent high-intensity interval-running capacity compared with CHO alone. In a repeated-measures design, 6 men performed a glycogen-depleting exercise protocol until volitional exhaustion in the morning. Immediately after and at 1, 2, and 3 hr postexercise, participants consumed 1.2 g/kg body mass CHO of a 15% CHO solution, a similar CHO solution but with addition of 8 mg/kg body mass of caffeine (CHO+CAFF), or an equivalent volume of flavored water only (WAT). After the 4-hr recovery period, participants performed the Loughborough Intermittent Shuttle Test (LIST) to volitional exhaustion as a measure of high-intensity interval-running capacity. Average blood glucose values during the 4-hr recovery period were higher in the CHO conditions \((p < .005)\) than in the WAT trial \((4.6 \pm 0.3 \text{ mmol/L})\), although there was no difference \((p = .46)\) between CHO \((6.2 \pm 0.8 \text{ mmol/L})\) and CHO+CAFF \((6.7 \pm 1.0 \text{ mmol/L})\). Exercise capacity during the LIST was significantly longer in the CHO+CAFF trial \((48 \pm 15 \text{ min})\) than in the CHO \((32 \pm 15 \text{ min}, p = .04)\) and WAT conditions \((19 \pm 6 \text{ min}, p = .001)\). All 6 participants improved performance in CHO+CAFF compared with CHO \((95\% \text{ CI for mean difference } = 1–32 \text{ min})\). The study provides novel data by demonstrating that adding caffeine to postexercise CHO feeding improves subsequent high-intensity interval-running capacity, a finding that may be related to higher rates of postexercise muscle glycogen resynthesis previously observed under similar feeding conditions.

**Keywords:** recovery, muscle glycogen, exercise capacity

It is common practice for athletes in a variety of sports to train twice per day, often adopting a training schedule with a morning and afternoon training session interspersed with only 3–6 hr of recovery. This is particularly the case for athletes involved in team sports (such as soccer, rugby, etc.), especially during the preseason period, when the development of sport-specific fitness over an intense 4- to 6-week period is the main training goal (Bangsbo, Mohr, & Krustrup, 2006). Given the well-known relationship between preexercise glycogen concentration and exercise capacity (Bergstrom, Hermansen, Hultman, & Saltin, 1967), the major challenge for sports nutritionists in these situations has therefore traditionally been to implement nutritional interventions that promote maximal rates of muscle glycogen resynthesis to maintain the desired training intensity for the subsequent afternoon training session. Indeed, performing repetitive training sessions in conditions of reduced carbohydrate (CHO) availability could lead to a potential detraining effect as absolute training intensity may be compromised (Yeo et al., 2008), as well as other associated problems such as loss of lean muscle mass through augmented protein oxidation (Howarth et al., 2010) and impaired immune function (Gleeson, 2007).

In considering factors that determine postexercise muscle glycogen resynthesis rates, the timing (Ivy, Katz, Cutler, Sherman, & Coyle, 1988), amount (van Loon, Saris, Kruijshoop, & Wagenmakers, 2000), and glycemic index (Burke, Collier, & Hargreaves, 1993) of CHO consumed have all been identified as key determinants. In this regard, it is now generally accepted that feeding high-glycemic CHO immediately postexercise at an ingestion rate of 1.2 g · kg body mass \(^{-1} \cdot \text{hr}^{-1}\) is the optimal protocol to promote short-term (i.e., several hours) muscle glycogen resynthesis rates in the region of 40–45 mmol · kg dry weight \(^{-1} \cdot \text{hr}^{-1}\) (Jentjens & Jeukendrup, 2003). However, more recent evidence has emerged demonstrating that coingesting caffeine (8 mg/kg body mass) with this feeding protocol augments glycogen resynthesis rates to 60 mmol · kg dry weight \(^{-1} \cdot \text{hr}^{-1}\) (Pedersen et al., 2008). Although the precise mechanisms for these effects are currently unknown, it is important to note that these rates of muscle glycogen resynthesis are the highest ever reported in the literature, with the exception of glucose-infusion protocols (Bergstrom & Hultman, 1967). Given the apparent ability of coingestion of caffeine with CHO to augment muscle glycogen storage and the intrinsic link between preexercise glycogen stores and exercise...
intensity or capacity (Bergstrom et al., 1967; Yeo et al., 2008), it is therefore tempting to suggest that this feeding protocol may augment exercise capacity during a training session commenced within 3–4 hr of completion of an initial training session that posed considerable glycogen depletion, although this remains to be formally tested.

With this in mind, the aim of the current study was to test the hypothesis that coingestion of caffeine with CHO (CHO+CAF) during a 4-hr recovery period after glycogen-depleting exercise augments subsequent high-intensity interval-running capacity compared with ingesting CHO alone. We employed the Loughborough Intermittent Shuttle Running Test (LIST) as our test of high-intensity interval-running capacity, given its reliability and validity as a field test simulating activity patterns inherent to team sports such as soccer (Nicholas, Nuttall, & Williams, 2000).

**Materials and Methods**

**Subjects**

Six recreationally active men (age 21 ± 1 years, height 1.78 ± 0.07 m, body mass 74.5 ± 8.4 kg, maximal oxygen uptake \[\text{VO}_{2\text{max}}\] 56 ± 1 ml · kg\(^{-1}\) · min\(^{-1}\)) volunteered to take part in this study. All gave written and informed consent after details of the study procedures were fully explained. No subject had a history of smoking or cardiovascular and metabolically related disease, and none were under any pharmacological treatment during the course of the study. All subjects were nonhabitual caffeine users and refrained from exercise and consuming alcohol or, finally, an equivalent amount of flavored water (WAT; Volvic, Touch of Fruit, 1.2 kcal/100 ml, Danone Waters, UK). This combination of dosage and timing of caffeine ingestion has been previously shown to raise plasma caffeine levels from undetectable levels before ingestion to 77 ± 11 μM 4 hr after the initial ingestion point (Pedersen et al., 2008). Regardless of condition, drinks were consumed within 5 min of the cessation of exercise and again at 60, 120, and 180 min postexercise. The amount of CHO consumed was based on recommendations to optimize restoration of muscle glycogen stores during the immediate recovery (0–4 hr) after exercise (Jentjens & Jeukendrup, 2003). All solutions were administered by independent laboratory technicians with no knowledge of the study aims. For the noncaffeine trials, subjects consumed visually identical placebo capsules consisting of an equivalent mass of glucose (glucose, 100% dextrose monohydrate; Thornton & Ross Ltd., Huddersfield, England). At 10 min postadministration of each solution, subjects rated gastrointestinal discomfort on a scale of 1 to 10 (1 = no discomfort, 10 = severe discomfort). After the 4-hr recovery period (at approximately 2 p.m.), subjects reported to an indoor running track to perform the LIST (Nicholas et al., 2000) to volitional fatigue to provide a measure of high-intensity interval-exercise capacity. Fingertip capillary blood samples (5 μl) were obtained immediately before and after completion of both exercise protocols, as well as at 30-min intervals throughout the 4-hr recovery period.

**Assessment of VO\(_{2\max}\)**

At least 7–10 days before the first experimental trial, subjects performed a continuous incremental treadmill protocol run to volitional exhaustion on a motorized treadmill (h/p/cosmos, Pulsar, Nussdorf-Traunstein, Germany) to determine VO\(_{2\max}\). The test protocol commenced with a 2-min stage at a treadmill speed of 10 km/hr followed by 2-min stages at 12, 14, and 16 km/hr. After completion of the 16-km/hr stage, the treadmill was inclined by 2% every 2 min thereafter until volitional exhaustion. Expired gas was collected for the last 30 s of every 2-min interval using Douglas bags. The expired gas was analyzed using a paramagnetic gas analyzer (Sybron-Taylor, model 5200, Servomex Ltd., UK). VO\(_{2\max}\) was assumed as the highest VO\(_2\) value obtained in any 30-s period and was stated as being achieved by the following end-point criteria: heart rate within 10 beats/min of age-predicted maximum, respiratory-exchange ratio >1.1, and plateau of VO\(_2\) despite increasing workload. The VO\(_2\) relationship with running speed was used to determine the appropriate running speeds for the experimental trials described next.

**Exercise Protocol 1: Glycogen-Depleting Run**

On arrival at the laboratory, subjects had their nude body mass and height measured (Seca 703, Gmbh & Co., Germany) and prerun blood samples taken before performing an intermittent run to volitional fatigue on
a motorized treadmill (h/p/cosmos, Pulsar, Nussdorf-Traunstein, Germany). After a 5-min warm up, they commenced running for 2 min at a treadmill speed corresponding to 90% of their VO2max, followed immediately by 2 min recovery at 50% VO2max. This work–recovery protocol was maintained until subjects were unable to complete 2 min of running at 90% VO2max. At this time, the treadmill speed was lowered to 80% VO2max with the same work:recovery ratio. When subjects were unable to maintain this intensity, the treadmill speed was lowered further to 70% and finally 60% of their VO2max. When the subjects were unable to complete 2 min of running at a speed corresponding to 60% of their VO2max, the exercise was terminated and a postexercise capillary blood sample was collected. Heart rate (Polar FS1, Kempele, Finland) was recorded continuously throughout exercise, and blood samples taken. Water was consumed ad libitum in a drinking pattern that was replicated for subsequent trials. The intent of this prolonged exhaustive exercise bout was to induce glycogen depletion in both Type I and Type II muscle fibers.

**Exercise Protocol 2: Exercise-Capacity Test**

After the 4-hr recovery period (at approximately 2 p.m.), subjects reported to an indoor running track and, after having had a preexercise capillary blood samples taken, they then performed the LIST (Nicholas et al., 2000) to volitional fatigue as a measure of high-intensity interval-running capacity. Subjects were deemed fatigued when they were unable to complete two consecutive shuttles and immediately had their test time to exhaustion recorded and postexercise capillary blood samples taken. Water was consumed ad libitum in each 3-min recovery period throughout the duration of the LIST, with the pattern of consumption repeated for the subsequent trials. At least 3 days after completion of the initial VO2max test and 5 days before the first trial, all subjects were familiarized with the protocol running speeds by completing ~10 min of Parts A and B to ensure subject compliance when performing the LIST. Subjects were unaware of the time or distance they had covered for either of the exercise protocols until the end of the study.

**Dietary Controls**

Diet and exercise diaries were used to standardize food intake and physical activity for 48 hr before the subjects’ first experimental trial and to verify compliance. Nutritional analysis revealed that subjects’ mean daily energy intake was 2,238 ± 584 kcal (53% ± 15% CHO, 32% ± 14% fat, and 14% ± 3% protein). All subjects repeated this dietary and activity pattern in the 48 hr preceding their remaining two trials to ensure similar preexercise muscle glycogen levels between trials.

**Blood Sampling**

Blood glucose and lactate concentrations were obtained via finger-prick capillary sampling using a 1.8-mm safety lancet (Sarstedt, Aktiengesellschaft & Co., Sweden) after sterilization using a preinjection medical swab (Medlock Medical Ltd., Oldham). Five microliters of whole blood were immediately analyzed for glucose and lactate concentration using an automated glucose analyzer (HemoCue Glucose 201+, Angelholm, Sweden) and lactate analyzer (Lactate Pro, Arkay, Shiga, Japan), respectively.

**Statistical Analysis**

Data were analyzed by one-way and/or two-way withinsubject analysis of variance (ANOVA) with repeated measures (version 15 for Windows, SPSS Inc., Chicago, IL). Before analysis, all data were analyzed for normal distribution using the Shapiro–Wilk test. Differences in exercise- and recovery-related variables (i.e., blood lactate and glucose concentration and gastrointestinal discomfort ratings) were analyzed using a two-way repeated-measures general linear model in which the within factors were time (i.e., exercise and recovery duration) and condition (i.e., CHO, CHO+CAFF, and WAT). Differences in exercise capacity (i.e., time to exhaustion) between conditions were analyzed using a one-way repeated measures general linear model. Where there was a significant difference, a paired t test using Bonferroni corrections for multiple comparisons was employed for post hoc analysis. All values are expressed as M and SD, with the statistical level of significance established at p < .05. In relation to our primary outcome variable of exercise capacity, we also report uncertainty of outcomes as 95% confidence intervals (95% CI) and make probabilistic magnitude-based inferences about the true (large-sample) values of outcomes by qualifying the likelihood that the true effect represents a substantial change, according to Batterham and Hopkins (2006).

**Results**

**Physiological and Metabolic Responses to Glycogen-Depleting Exercise**

Exercise times to exhaustion for the glycogen-depleting run in the CHO, CHO+CAFF, and WAT trials were 82 ± 13, 83 ± 11, and 86 ± 9 min, respectively, with no significant difference between conditions (p = .128). Exercise significantly increased blood lactate values (p = .022) for the CHO (preexercise 1.3 ± 0.4, postexercise 2.7 ± 1.1 mmol/L), CHO+CAFF (preexercise 1.3 ± 0.8, postexercise 4.2 ± 3.0 mmol/L) and WAT trials (preexercise 1.1 ± 0.2, postexercise 2.7 ± 0.6 mmol/L), although there were no significant differences between
conditions \((p = .220)\). Average heart rates during exercise also displayed no significant difference \((p = .246)\) between conditions \((165 \pm 8, 162 \pm 10, \text{and} 159 \pm 11 \text{beats/min for the CHO, CHO+CAFF, and WAT trials, respectively})\). Taken together, these data suggest that the physiological stress imposed by the glycogen-depleting exercise protocol was similar between trials.

**Response of Plasma Glucose and Rates of Gastrointestinal Discomfort to Nutritional Interventions During the 4-hr Recovery**

Blood glucose levels were significantly higher throughout the 4-hr recovery period in the CHO and CHO+CAFF trials than in the WAT condition \((p = .0001 \text{and} .005, \text{respectively, see Figure 1})\), but there was no significant difference in blood glucose concentrations between the CHO and CHO+CAFF conditions \((p = .463)\). Mean blood glucose concentrations over the 4 hr of recovery were 6.2 ± 0.8, 6.7 ± 1.0, and 4.6 ± 0.3 mmol/L during the CHO, CHO+CAFF, and WAT trials, respectively. Rates of gastrointestinal discomfort 10 min after each of the four feeding points were significantly higher in the CHO and CHO+CAFF trials than in the WAT condition \((p = .0001 \text{for both comparisons, see Table 1})\). There was no significant difference, however, in gastrointestinal discomfort between CHO and CHO+CAFF conditions \((p = .688)\).

**Total Exercise Time to Exhaustion and Metabolic Responses to the Exercise-Capacity Protocol**

Total exercise times to exhaustion during the LIST protocol (including recovery time between Part A exercise bouts) for the CHO, CHO+CAFF, and WAT trials were 32 ± 15 (95% CI 16–47 min), 48 ± 15 (95% CI 32–63 min), and 19 ± 6 min (95% CI 13–25 min), respectively (see Figure 2). Participants exercised significantly longer in the CHO+CAFF trial than in the CHO \((p = .044)\) and WAT \((p = .001)\) trials. The 95% CI for mean differences in exercise capacity between CHO+CAFF versus CHO and CHO+CAFF versus WAT were 1–32 and 18–40 min, respectively. All 6 individuals demonstrated better performance in the CHO+CAFF trial than in the CHO-only trial (range 3–35 min). Differences in exercise capacity between CHO and WAT trials approached statistical significance \((p = .06)\) and can be interpreted as physiologically significant given that the 95% CI for mean differences between trials was –1 to 26 min.

![Figure 1](image)

*Figure 1 — Blood glucose concentrations during the 4-hr recovery period for the carbohydrate (CHO), CHO plus caffeine (CHO+CAFF), and water (WAT) trials. *Significant difference from WAT, \(p < .05\).*
Indeed, 5 of 6 participants displayed better performance in the CHO trial than in the WAT trial (range −1.5 to 33 min). Exercise significantly increased blood lactate values ($p = .002$) for the CHO (preexercise $1.3 \pm 0.6$, postexercise $4.4 \pm 0.7$ mmol/L), CHO+CAFF (preexercise $1.4 \pm 0.4$, postexercise $6.9 \pm 5.4$ mmol/L), and WAT trials (preexercise $1.4 \pm 0.5$, postexercise $7.6 \pm 4.7$ mmol/L), although there were no significant differences between conditions ($p = .443$).

**Discussion**

The aim of the current study was to determine whether adding caffeine to postexercise CHO feeding improves subsequent high-intensity interval-running capacity compared with the ingestion of CHO alone. Confirming our hypothesis, we provide novel data by demonstrating that ingesting 8 mg/kg body mass of caffeine (administered in two equal doses of 4 mg/kg body mass immediately postexercise and 2 hr postexercise) in combination with a CHO feeding strategy known to optimize muscle glycogen resynthesis improves high-intensity running capacity by 50% when undertaken 4 hr after an initial training session. All 6 participants demonstrated improved exercise capacity in the CHO+CAFF trial compared with the CHO trial, and the 95% CI for mean differences between conditions was 1–32 min. In addition to a statistically significant effect, these data can therefore also be interpreted qualitatively as beneficial in terms of practical physiological significance (Batterham & Hopkins, 2006). As...
such, we consider our data to be of practical application for athletes who regularly complete two high-intensity training sessions per day when recovery time between sessions is limited to several hours.

Although the precise mechanisms underpinning the ergogenic effects of caffeine on exercise performance are not fully understood, based on recent research from Pedersen et al. (2008), it is reasonable to suggest that the enhanced performance effect observed here may be a result of increased rates of muscle glycogen resynthesis. Pedersen et al. used a feeding protocol similar to that adopted here and observed glycogen synthesis rates of 60 mmol · kg dry weight⁻¹ · hr⁻¹ when caffeine was coingested, compared with rates of 40 mmol · kg dry weight⁻¹ · hr⁻¹ when CHO alone was consumed. At the end of the 4-hr recovery period, total glycogen resynthesis was therefore 80 mmol/kg greater in the CHO+CAF trial than in the CHO-only condition. Based on known glycogen-utilization rates of the vastus lateralis muscle of males (albeit in conditions of high preexercise muscle glycogen) when performing the LIST (approximately 2.5 mmol · kg⁻¹ · min⁻¹; Nicholas, Tsintzas, Boobis, & Williams, 1999), it could be estimated that an extra 80 mmol/kg of available glycogen may correspond to an enhanced exercise capacity of approximately 30 min. However, because our subjects commenced the LIST after undertaking an intense morning training session (thereby reducing muscle glycogen stores) and muscle glycogen utilization is reduced in conditions of reduced preexercise muscle glycogen (Hargreaves, McConell, & Proietto, 1995), as well as the differing training status of subjects between studies (hence potentially affecting glycogen resynthesis rates), the enhanced running time of 16 min (95% CI for mean difference of 1–32 min) observed in the CHO+CAFF condition appears in agreement with the enhanced resynthesis rates reported by Pedersen et al. (2008). We purposely implemented a running (as opposed to cycling) depletion protocol to reflect the activity patterns experienced by athletes who compete in intermittent high-intensity team sports. Although we acknowledge that we cannot conclusively comment on the degree of glycogen depletion induced by our morning exercise protocol, experimental evidence suggests that our participants were indeed glycogen depleted because they were unable to complete Part A of the LIST, even in the CHO conditions (e.g., exercise capacity of 32 and 48 min in CHO and CHO+CAFF, respectively). Furthermore, in the WAT trial, mean exercise capacity was only 20 min, which is in marked contrast to the ability of recreationally active males to readily complete Part A under normal dietary conditions (Nicholas et al., 2000).

In addition, caffeine’s proposed mechanisms of action on the central nervous system (CNS) should not be disregarded as a potential mechanism underpinning improved exercise capacity. Indeed, caffeine may act directly on the CNS by stimulating the secretion of β-endorphin (Arnold, Carr, Togasaki, Pian, & Martin, 1982), a hormone capable of modifying the perception of pain via reducing discomfort through its analgesic properties (Grossman & Sutton, 1985), thus enabling subjects to exercise for longer. Moreover, Laurent et al. (2000) observed that when caffeine was ingested at a dose of 6 mg/kg body mass, significant increases in plasma β-endorphin concentration were evident after 2 hr of cycling at 65% VO2peak and a subsequent bout of high-intensity sprint activity. Using a similar dosage, Cole et al. (1996) observed increased work output during 30 min of exercise that participants undertook at self-selected power outputs corresponding to a clamped perception of effort (commenced 1 hr after caffeine ingestion) compared with a placebo trial. In this way, caffeine appears to increase power output by lowering the perception of fatigue and effort, and this mechanism may have contributed to the ergogenic effect observed here.

In addition to its effects on the CNS, it is possible that caffeine exerted a direct effect on the contracting muscles by altering substrate utilization during exercise. In this regard, numerous studies (Erickson, Schwartzkopf, & McKenzie, 1987; Ivy, Costill, Fink, & Lower, 1979; Spriet et al., 1992) have attributed improvements in performance to caffeine-induced augmentation of lipolysis and subsequent fat oxidation, thus potentially sparing muscle glycogen (Erickson et al., 1987). Indeed, with a dosage similar to that adopted here, Cole et al. (1996) observed increased circulating free fatty acids and glycerol during 30 min of exercise performed 1 hr after caffeine ingestion compared with placebo, despite the fact that exercise in the caffeine trial was associated with higher self-selected absolute exercise intensities. Unfortunately, we did not obtain indications of lipolysis, free fatty acid availability, or substrate oxidation because of the difficulties of obtaining these measures during exhaustive shuttle running on an indoor running surface, and, as such, we acknowledge this as a limitation of our study.

In conclusion, we provide novel data demonstrating that adding caffeine to postexercise CHO feeding improves subsequent high-intensity interval-running capacity compared with CHO feeding alone. Although we cannot currently offer precise mechanisms underpinning this improved exercise capacity, it may be related to improved rates of muscle glycogen resynthesis, given recent data (Pedersen et al., 2008) demonstrating enhanced glycogen resynthesis rates induced with a feeding protocol similar to that employed here. Furthermore, the commonly cited ergogenic mechanisms of caffeine action, such as its effects on the CNS and modifying muscle metabolism through a glycogen-sparing effect, cannot be excluded. Future studies should therefore perform additional measurements to fully test these hypotheses. Finally, whether lower doses of additive caffeine with CHO can produce similar enhanced performance effects also warrants investigation, given the disadvantages of caffeine in other important aspects of recovery such as quantity and quality of sleep. Such research is also warranted given that the high dosage of caffeine administered here in capsule format may not always be achievable in real-world sporting situations.
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References


