Effect of Caffeine on Sport-Specific Endurance Performance: A Systematic Review

Matthew S. Ganio, Jennifer F. Klau, Douglas J. Casa, Lawrence E. Armstrong, and Carl M. Maresh

Human Performance Laboratory, Department of Kinesiology, University of Connecticut, Storrs, Connecticut

Abstract

Ganio, MS, Klau, JF, Casa, DJ, Armstrong, LE, and Maresh, CM. Effect of caffeine on sport-specific endurance performance: a systematic review. *J Strength Cond Res* 23(1): 315–324, 2009—Endurance athletes often ingest caffeine because of its reported ergogenic properties. Although there are a vast number of studies quantifying caffeine's effects, many research studies measure endurance performance using a time-to-exhaustion test (subjects exercise at a fixed intensity to volitional exhaustion). Time-to-exhaustion as a performance measure is not ideal because of the high degree of measurement variability between and within subjects. Also, we are unaware of any endurance sports in which individuals win by going a longer distance or for a longer amount of time than their competitors. Measuring performance with a time-trial test (set distance or time with best effort) has high reproducibility and is more applicable to sport. Therefore, the purpose of this review was to critically and objectively evaluate studies that have examined the effect of caffeine on time-trial endurance (>5 minutes) performance. A literature search revealed 21 studies with a total of 33 identifiable caffeine treatments that measured endurance performance with a time-trial component. Each study was objectively analyzed with the Physiotherapy Evidence Database (PEDro) scale. The mean PEDro rating was 9.3 out of 10, indicating a high quality of research in this topic area. The mean improvement in performance with caffeine ingestion was 3.2 ± 4.3%; however, this improvement was highly variable between studies (−0.3 to 17.3%). The high degree of variability may be dependent on a number of factors including ingestion timing, ingestion mode/vehicle, and subject habituation. Further research should seek to identify individual factors that mediate the large range of improvements observed with caffeine ingestion. In conclusion, caffeine ingestion can be an effective ergogenic aid for endurance athletes when taken before and/or during exercise in moderate quantities (3–6 mg·kg^{-1} body mass). Abstaining from caffeine at least 7 days before use will give the greatest chance of optimizing the ergogenic effect.

Key Words aerobic exercise, competition, ergogenic, racing, theophylline

Address correspondence to Matthew S. Ganio, matthew.ganio@uconn.edu.

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Introduction

Caffeine (CAF) is commonly ingested by athletes because of its reported ergogenic effects (23). Caffeine has been proposed to improve physical performance by acting independently, or concurrently, via 3 different mechanisms: 1) an increased mobilization of intracellular calcium, 2) an increase in free fatty acid oxidation, and 3) serving as an adenosine receptor antagonist in the central nervous system (59). Early research by Costill et al. (16) suggested that the ergogenic effect of CAF with aerobic exercise was related to an increase in fatty acid oxidation and subsequent sparing of muscle glycogen. However, recent research and reviews conclude that CAF affects endurance performance largely through its antagonist effect on adenosine receptors in the brain (20,40). Acting through this mechanism, CAF may modulate central fatigue and influence ratings of perceived exertion, perceived pain, and levels of vigor, all of which may lead to performance improvements (39,51).

A recent meta-analysis by Doherty and Smith (23) has quantified the effect of CAF on endurance time to exhaustion and on short-term, high-intensity exercise protocols. Caffeine was found to improve endurance time to exhaustion (effect size [ES] = 0.63) to a greater degree than short-term performance (ES = 0.16). Exercise is generally classified as endurance activity (vs. short-term) when the majority of energy is produced through aerobic (vs. anaerobic) pathways (55). A higher percentage of total energy is produced aerobically after about 3 minutes of exercise, and this is independent of exercise mode. Although Doherty and Smith (23) categorize the different protocols examined, they never specify their criteria for classifying a protocol as "endurance" or "short-term." They identify several protocols lasting >5 minutes as "short-term, high intensity" (1,10).

To isolate the effect of CAF on performance, CAF capsules are commonly used as the mode of delivery (1,6,7), but other forms of CAF delivery include gum (49), carbohydrate-electrolyte (CE) solutions (18,44,57), and coffee (65). There is the possibility that these substances (e.g., carbohydrate) may contribute to CAF's direct ergogenic actions. Despite isolating the effect of CAF (e.g., conducting a trial with carbohydrate only and another with carbohydrate plus CAF), many studies delivering CAF in modes other than capsules have not been included in reviews and meta-analyses (23). However, it is important to evaluate the findings from these studies because CAF used in sport is commonly consumed in modes other than capsules (21). For example, in a recent survey of 2005 Ironman Triathlon World Championship athletes, 78% of the respondents planned to use caffeinated cola drinks and 42% planned to use caffeinated gels (21).

The ergogenic effect of CAF is most consistently observed when performance is measured with a "test-to-exhaustion" protocol (i.e., performance is measured as time to volitional exhaustion while exercising at a fixed intensity [% $\dot{V}O_2max$]) (23). Unfortunately, this type of protocol may not be ideal because a small change in an individual's ability to increase power results in a large change in time to exhaustion and a high coefficient of variation (33). Therefore, improvements may be observed despite a large amount of measurement variability and inflation of type I error (33). A recent study by Laursen et al. (45) further suggests that there is a greater coefficient of variation when subjects perform a test to exhaustion vs. a time trial. Further, a test to exhaustion does not elucidate the true performance effect of CAF (38) because we are unaware of any endurance sport in which individuals win by going a longer distance or for a longer amount of time than their competitors. Endurance/aerobic sport requires competitors to complete a set distance or amount of work in the shortest time possible (time trial) or a maximal amount of work in a fixed amount of time. Therefore, studies examining the ergogenic effect of CAF using a time-trial protocol are more applicable to athletes.

The purpose of this systematic review is to analyze critically the effect of CAF on performance in practical endurance sport settings. This includes studies that have measured performance with a time-trial protocol ≥5 minutes in duration. We have also included studies using different modes of CAF administration but in which the effect of CAF has been appropriately isolated.

Methods

In August 2007, potential studies were identified by searching proQuest, SportDiscus, MEDLINE, and Scopus using the following search terms in varying combinations: caffeine, caffeinated, coffee, theophylline, paraxanthine, theobromine, endurance, and exercise. Articles were then prescreened and cross-referenced to identify those containing time-trial components. Review articles and book chapters published since 1985 that pertained to CAF and exercise performance also were cross-referenced for relevant articles (19,22–25, 28,30,40,43,47,52,54,56,59,60).

Experimental Approach to the Problem

Inclusionary Criteria. Human studies of men and women were included if the effect of CAF administered in any form could be isolated and if the performance protocol lasted ≥5 minutes and had any component of a time trial. This included studies in which performance was measured as the time to complete a set distance or maximal amount of work completed in a fixed amount of time.

Although a recent meta-analysis (23) has examined the effects of CAF on performance, this review includes studies published since that meta-analysis (9,18,48,49,61), those that were conducted in a field setting (7,9,12,61), and those that used modes of CAF delivery other than capsules (17,18,34–36,44,48,50,62,64,65). Although it could be argued that other factors may confound results in these studies, these studies are applicable to sports in which athletes often ingest CAF along with other substances (21). Studies using modes of CAF ingestion other than capsules were only included if the independent effects of CAF could be distinguished (i.e., a CE solution was used with and without CAF).

Studies examining the effects of CAF in combination with factors other than exercise (e.g., altitude, sleep deprivation) were only used if there was a control condition with placebo and CAF trials. Dissertations were included only if the same data were not presented in a peer-reviewed published paper. Although double-blind studies are ideal, studies were included if they at least used single-blind (blind to participants) CAF administration.

Exclusionary Criteria. Studies in which performance was measured by time to exhaustion were not included. Although graded exercise tests (i.e., $\dot{V}O_2max$ tests) last longer than 5 minutes, these tests are another form of test to exhaustion (45).

Physiotherapy Evidence Database Scale. A systematic review was conducted using the Physiotherapy Evidence Database (PEDro) scale to rate each article. Although other type of reviews exist (e.g., meta-analysis), some statisticians argue that they are susceptible to bias and other problems (27,50). The PEDro scale was developed by the Centre for Evidence-Based Physiotherapy (53). This rating scale was deemed acceptable because of its ability to objectively assess a study's internal validity. For example, the scale includes questions related to levels of subject and assessor blinding. This knowledge can have large implications when evaluating the effects of a treatment on performance. The PEDro scale is a 11-item checklist that yields a maximum score of 10 because no points are awarded for meeting the inclusionary criterion.

Each article was independently analyzed by 2 reviewers ($\kappa = 0.85$) and given a PEDro score. One article (17) included 2 studies (2 subject pools) that were analyzed independently and, thus, received 2 PEDro scores. Articles with discrepant component PEDro scores were analyzed by a third, independent reviewer. Any PEDro scores <6 were deemed unacceptable and were not used in analyses.

Results

The attrition of studies identified, prescreened, and selected for analysis is outlined in Figure 1. After preliminary screening, 26 studies were identified. One study published as 2 articles (one focusing on cognitive, the other on physiological measures) contained the same performance data (32,44); thus, the article focusing on cognitive measures was excluded (32). Another study (3) failed to meet the PEDro criterion score of 6, and one failed to isolate the effect of CAF (4). Two studies (48,49) tested the effects of CAF in combination with sleep deprivation but failed to test the effects without sleep deprivation and, thus, were excluded from analysis. One article (17) consisted of 2 studies with different subjects and analyses; therefore, it received 2 PEDro scores. Of the 21 remaining studies, 33 identifiable CAF treatments were employed (e.g., different CAF dosages in separate trials), as presented in Tables 1 and 2.

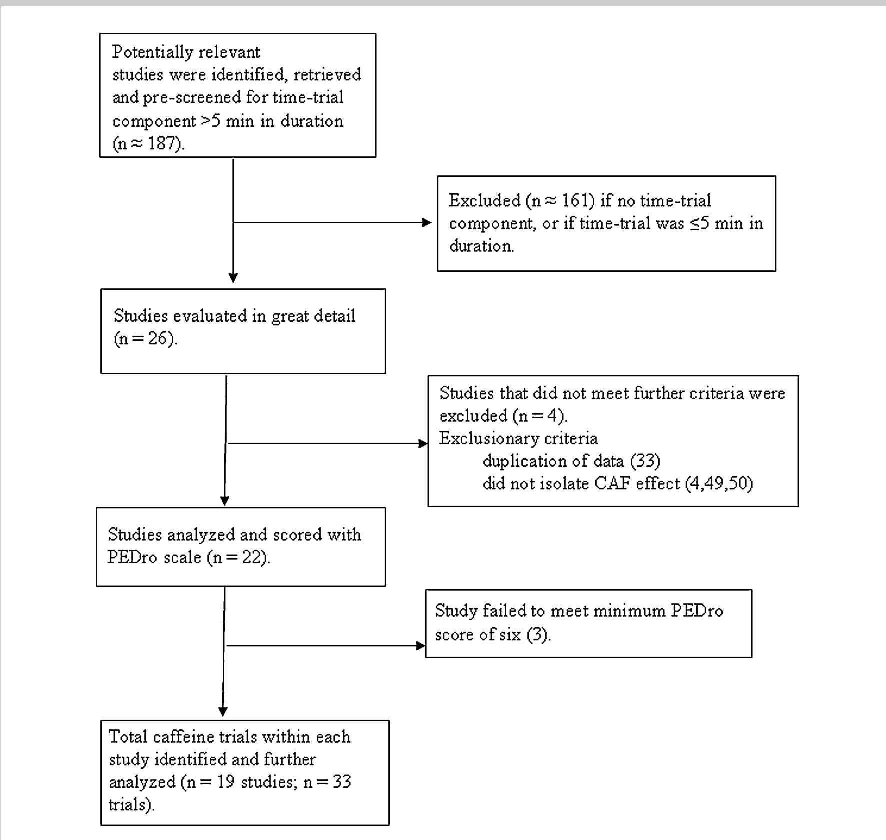

Figure 1. Decision tree for identifying, screening, and selecting studies for analyses.

The mean PEDro rating was a 9.3 out of 10. Sixteen of the studies scored a perfect 10. The most common PEDro item that studies failed to achieve was "blinding of therapists" and "blinding of assessors" (4 studies for each [17,34,35,61]). By failing to double-blind a study that is largely dependent on subject motivation and assessor encouragement, there is a risk that results are biased. It is important to note that failing to identify blinding procedures implies that blinding procedures were not used.

Twelve trials administered CAF in capsule form (i.e., with water) (mean ± *SD* improvement [mean improvement] = 2.9 ± 4.8%), and 13 trials examined the effects of CAF ingested along with a CE solution compared with a CE solution alone (mean improvement = 3.2 ± 3.8%). Four trials used CAF ingested with other substances (mean improvement = 2.9 ± 2.2%), and 4 did not report the mode of CAF delivery (mean improvement = 6.4 ± 7.4%). Interestingly, among trials in which CAF was ingested before and during exercise, the CAF was ingested along with a CE solution in all but 2 trials (Table 2).

Out of the 33 trials, 21 used cycling (mean improvement = 4.4 ± 5.0%), 6 used running (mean improvement = 0.9 ± 0.7%), 4 used rowing (mean improvement = 1.1 ± 0.3%), 1 used swimming (mean improvement = 1.7%), and 1 used cross-country skiing (mean improvement = 1.1%) as the mode of exercise. Sixteen trials used a set intensity before the time-trial component (mean improvement = 4.7 ± 5.6%); the other 17 did not (mean improvement = 1.8 ± 1.4%). Fourteen of the articles used time to complete a set distance as the performance measure (mean improvement = 1.1 ± 0.5%), 10 used maximum work produced in a fixed time (mean improvement = 4.3 ± 4.1%), and 9 used time to complete a set number of revolutions (W) while cycling (mean improvement = 5.2 ± 6.2%). Women were included in 10 of the 29 trials. Only 1 study (2 trials) tested only women subjects (1); the 8 remaining trials with women did not statistically analyze differences between sexes.

Independent of ingestion timing, the average performance improvement with CAF was 3.2 ± 4.3% over placebo.

TABLE 1. Effect of caffeine on performance when ingested before exercise.

Reference	Men (*n*)	Women (*n*)	Caffeine delivery mode	Volume and composition of fluid ingested	Caffeine time of administration (minutes before exercise)	Total caffeine ($mg \cdot kg^{-1}$)	Protocol	Total exercise time (min)	Improvement over placebo (%)	Pedro score
Jenkins et al. (37)	13	0	Capsule	450 ml of water before	60	1	15-min time trial after 15 min at 80% $\dot{V}O_2max$¶	30	−0.7	10
Cohen et al. (12)	5	2	Capsule	*Ad libitum* water throughout	60	9	21-km race§	89	−0.1	9
Anderson et al. (1)	0	8	Capsule	193.2 ml of water before	60	6	2-km time trial‖	8	0.7	10
Jacobson et al. (36)	8	0	"Fat meal"	1.3 L of water throughout	60	6	7-$kJ \cdot kg^{-1}$ time trial after 120 min at 70% $\dot{V}O_2max$¶	150	0.7	10
Cohen et al. (12)	5	2	Capsule	*Ad libitum* water throughout	60	5	21-km race§	89	0.8	9
Bruce et al. (10)	8	0	Capsule	3 $ml \cdot kg^{-1}$ of water before	60	9	2-km time trial‖	7	1.0*	10
Bridge and Jones (9)	8	0	Capsule	NR	60	3	8-km race§	32	1.2*	10
Anderson et al. (1)	0	8	Capsule	193.2 ml of water before	60	9	2-km time trial‖	8	1.3*	10
Bruce et al. (10)	8	0	Capsule	3 $ml \cdot kg^{-1}$ of water before	60	6	2-km time trial‖	7	1.3*	10
Wiles et al. (65)	18	0	Coffee	300 ml water before	60	2.5‡	1.5-km time trial§	5	1.4*	10
Bell et al. (6)	10	2	Capsule	NR	90	4	10-km time trial†§	45	1.7	10
Berglund and Hemmingsson (7)	10	4	Capsule	NR	60	6	20-km race#	60	1.7	9
MacIntosh and Wright (46)	7	4	Capsule	*Ad libitum* water prior	150	6	1.5-km time trial**	21	1.7*	10
Collomp et al. (13)	8	0	Capsule	NR	60	6	10-min time trial after 10 min at 95% $\dot{V}O_2max$¶	20	2.2	10
Jenkins et al. (37)	13	0	Capsule	450 ml of water before	60	3	15-min time trial after 15 min at 80% $\dot{V}O_2max$¶	30	2.9*	10
Cox et al. (17)	12	0	Capsule	2.7 L 6% carbohydrate-electrolyte solution throughout	60	6	7-$kJ \cdot kg^{-1}$ time trial after 120 min at 70% $\dot{V}O_2max$¶	148	3.4*	6
Jacobson et al. (36)	8	0	Carbohydrate meal	1.3 L of water throughout	60	6	7-$kJ \cdot kg^{-1}$ time trial after 120 min at 70% $\dot{V}O_2max$¶	150	4.1	10
Jenkins et al. (37)	13	0	Capsule	450 ml of water before	60	2	15-min time trial after 15 min at 80% $\dot{V}O_2max$¶	30	4.3*	10
Conway et al. (15)	8	0	Capsule	NR	60	6	~30-min time trial after 90 min at 68% $\dot{V}O_2max$¶	120	14.5	10

*Significant improvement over placebo trial; †each subject, by wearing a helmet and backpack, donned an additional 11 kg; ‡calculated by authors of the present study; §running; ‖rowing; ¶cycling; #cross-country skiing; **swimming. NR, not reported.

Table 2. Effect of caffeine on performance when ingested before and during exercise.

Reference	Men (*n*)	Women (*n*)	Fluid composition	Volume (L) and timing (min) of fluid ingestion	Amount ($mg \cdot kg^{-1}$) and timing (min) of caffeine ingestion	Total caffeine ($mg \cdot kg^{-1}$)	Protocol	Total exercise time (min)	Improvement over placebo (%)	Pedro score
Wemple et al. (64)	4	2	6% CES	P: 0.53 at 60 min S: 0.2 D: 0.2 from 20 to 220 min	P: 1.9 at 60 min S: 0.7 D: 0.7 from 20 to 220 min	8.7	500-revolution time trial after 180 min at 60% $\dot{V}O_2max$§	186	−0.3	10
van Nieuwenhoven et al. (61)	90	8	7% CES	P: 0 S: 0.15 D: 0.31 at 4.5, 9, and 13.5 km	P: 0 S: 0.31 D: 0.31 at 4.5, 9, and 13.5 km	1.25	18-km race‡	78	0.4	8
Eschbach (26)	11	0	6% CES	P: 0 S: 0 D: 0.25 every 15 min	P: 6 at 180 min S: 0 D: 3 at 60 min	9	5-km time trial after 240 min at 55% $\dot{V}O_2max$§	250	0.8	10
Hunter et al. (34)	8	0	7% CES	P: 0 S: 0 D: 0.15 every 15 min	P: 6 at 60 min S: 0 D: 0.33 every 15 min	9.3	100-km time trial with 9 sprints throughout§	158	1.3	7
Kovacs et al. (44)	15	0	7% CES	P: 0.58 at 60 min S: 0 D: 0.22 at 20 and 40 min	P: 0.7 at 60 min S: 0 D: 0.7 at 20 and 40 min	2.1	60-min time trial§	60	1.8	10
Cox et al. (17)	8	0	6% CES	P: 0 S: 0 D: 0.34 every 20 min	P: 0 S: 0 D: 0.95 at minutes 80 and 100 during time trial	1.9	7-$kJ \cdot kg^{-1}$time trial after 120 min at 70% $\dot{V}O_2max$§	148	1.8*	7
Cox et al. (17)	8	0	6% CES	P: 0 S: 0 D: 0.34 every 20 min	P: 0 S: 0 D: 0.95 at minutes 80 and 100 during time trial†	1.9	7-$kJ \cdot kg^{-1}$time trial after 120 min at 70% $\dot{V}O_2max$§	148	2.4*	7
Cox et al. (17)	12	0	6% CES	P: 0 S: 0 D: 0.34 every 20 min	P: 0 S: 0 D: 1 every 20 min	6	7-$kJ \cdot kg^{-1}$time trial after 120 min at 70% $\dot{V}O_2max$§	148	3.1	7
Ganio (personal communication, August 12, 2007)	14	0	6% CES	P: 0 S: 0.44 D: 0.22 every 15 min	P: 0 S: 1.2 D: 0.5 every 15 min	5.85	15-min time trial after 120 min at 60 and 75% $\dot{V}O_2max$§	135	3.6	10

(*Continued on next page*)

Kovacs et al. (44)	15	0	7% CES	P: 0.58 at 60 min S: 0 D: 0.22 at 20 and 40 min	P: 1.1 at 60 min S: 0 D: 1.1 at minutes 20 and 40	3.2	60-min time trial§	60	4.2*	10
Kovacs et al. (44)	15	0	7% CES	P: 0.58 at 60 min S: 0 D: 0.22 at 20 and 40 min	P: 1.5 at 60 min S: 0 D: 1.5 at minutes 20 and 40	4.5	60-min time trial§	60	4.2*	10
Ivy et al. (35)	7	2	Lemonade	NR	P: 3.6 at 60 min S: 0 D: 0.4 every 15 min	7.2	120-min time trial§	120	5.3*	8
Cureton et al. (18)	16	0	6% CES	P: 0 S: 0.44 D: 0.22 every 15 min	P: 0 S: 1.2 D: 0.5 every 15 min	5.3	15-min time trial after 120 min at 60 and 75% $\dot{V}O_2max$§	135	15.0*	10
Conway et al. (15)	8	0	Water	P: 0 S: 0 D: 1.4 *ad libitum*	P: 3 at 60 min S: 0 D: 3 at 45 min	6	~30-min time trial after 90 min at 68% $\dot{V}O_2max$§	120	17.3	10

*Significant improvement over placebo trial; †6% carbohydrate-electrolyte solution (CES) was substituted for 11% CES at these time points; ‡running; §cycling. NR, not reported; P, prior to exercise; S, start of exercise; D, during exercise.

The median improvement with CAF was 1.7%. Thirty of the 33 trials showed positive improvements in performance with CAF, but only 15 were statistically significant ($p < 0.05$). One study with 2 different CAF trials observed large performance improvements (14.5 and 17.3%) but were not statistically significant, possibly because of a type II error (15). Another study (18) observed a large, significant improvement (15%) over placebo. This improvement may be attributable to the combination of repeated CAF ingestion throughout the exercise protocol and/or the unique submaximal protocol in which subjects alternated between 60 and 75% $\dot{V}O_2$max for 120 minutes before starting a 15-minute time trial.

Caffeine ingested before exercise resulted in a mean performance improvement of 2.3 ± 3.2% (Figure 2). Performance was improved 4.3 ± 5.3% when CAF was ingested both before and during exercise (Figure 2). Total CAF ingestion does not explain these differences (mean = 5.3 mg·kg^{-1}, Table 1; 5.2 mg·kg^{-1}, Table 2). Further, the range of performance improvement is similar when CAF is ingested before exercise (−0.7 to 14.5%, Table 1) and when ingested before and during exercise (−0.3 to 17.3%, Table 2).

Discussion

The purpose of this systematic review was to critically evaluate studies that examined the effects of CAF on sport-specific endurance performance. We only reviewed articles that had time-trial components. This type of performance test is not only more valid in detecting treatment effects (33), but, more importantly, it is applicable to sport. For this same reason, we chose to include articles that were conducted in field settings or that used the treatment of CAF with other substances (i.e., CE solutions). Although ingesting CAF via capsules may prevent any interaction with other ingested foods or fluid, there is limited availability of ready-made CAF capsules that an athlete may ingest. There are quite a few studies examining CAF with CE solutions. This is not surprising because the American College of Sports Medicine recommends the use of CE solutions in long-duration exercise (58), a setting in which CAF is a commonly used ergogenic aid (23). Some have hypothesized that a high-carbohydrate diet may attenuate the increase in free fatty acids observed with CAF ingestion and, thus, modulate the ergogenic effect of CAF (63). This has not been observed in performance settings, and it likely has little effect. The ergogenic effect of CAF, especially in non–glycogen-limiting exercise, is thought to be more central in nature and not metabolic (20,40).

We found that CAF was equally ergogenic independent of delivery mode (mean = 2.9% improvement for water and 3.2% for CE solutions). Other forms of administration (i.e., gum, soft drink, coffee) have not been well studied, especially not with time-trial exercise protocols. The bioavailability of CAF via the gastrointestinal system is relatively quick (i.e., detected in the blood within 30 minutes), but the coingestion of CAF with other compounds may (17) or may not (29) slow down the appearance of CAF in the blood. However, absorption of CAF orally (via gum) is quicker than intestinally (via capsules) because of the presence of buccal mucosa in the mouth (41). Independent of mode, the breakdown of CAF is slow (i.e., half-life approximately 4–6 hours) (41). Critically examining studies using CAF delivery through modes other than capsules is important because many athletes use other modes of CAF delivery before and during competition (21).

The ingestion of CAF is similarly ergogenic regardless of ingestion approximately 60 minutes before or ingestion during exercise. The mean improvement is slightly greater when CAF is ingested both before and during exercise (4.3 ± 5.3%) compared with only before exercise (2.3 ± 3.2 %); this may be attributable to a different number of trials in each group (n = 14 and 19, respectively) and/or a large degree of variability. Regardless of administration timing, there is a

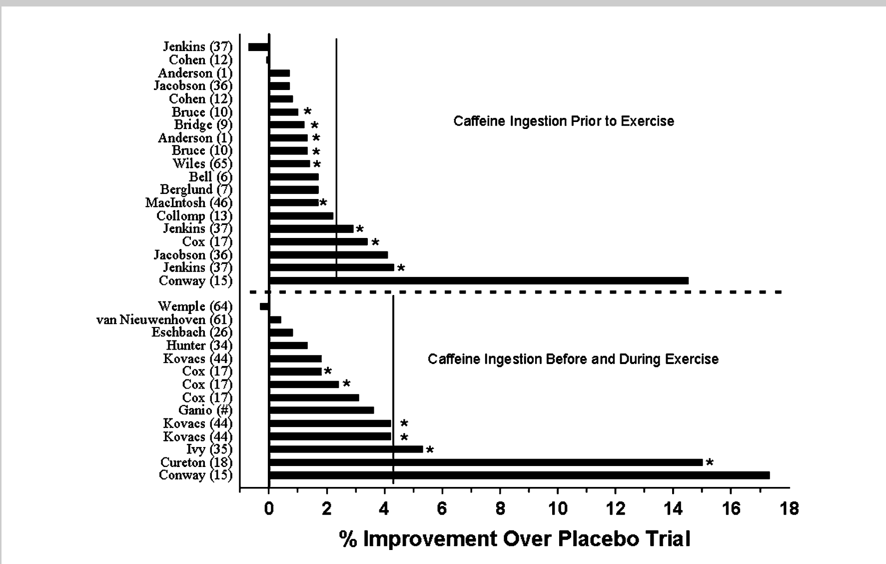

Figure 2. The effect of caffeine (CAF) on exercise performance when ingesting CAF before exercise (above horizontal hashed line) or before and during exercise (below horizontal hashed line). Vertical lines represent mean percent improvement of all studies (2.3 ± 3.2 and 4.3 ± 5.3% for above and below the hashed line, respectively). *Significantly different from placebo ($p < 0.05$). #Ganio (personal communication, August 12, 2007).

large range of improvements shown between studies (−0.7 to 17.3% improvement, Figure 2). Assuming an equal amount of total CAF, the timing of ingestion (before or during exercise) does not seem to be an important factor in eliciting the ergogenic effects of CAF. This is supported by studies that have conducted trials varying CAF ingestion timing and finding no differences in performance (15,17). Shorter races that do not usually involve rehydration during exercise may not be as conducive to CAF ingestion during exercise. On the other hand, CAF ingestion during exercise may be more feasible in longer-duration exercise when concurrent with fluid ingestion.

Degree of improvement with CAF does not seem to be consistently associated with mode of CAF delivery, timing, total exercise time, or the exercise mode employed (Tables 1 and 2). Total CAF ingested seems to be loosely associated with degree of improvement. It is generally observed that quantities above 3 $mg \cdot kg^{-1}$ body mass are needed for improvement. Quantities up to 6 $mg \cdot kg^{-1}$ are most commonly used, but this amount and greater amounts do not always result in performance improvements. Using a time-trial protocol, Bruce et al. (10) did not observe increased performance compared with placebo when increasing CAF ingestion from 6 to 9 $mg \cdot kg^{-1}$ body mass. In the studies we reviewed, 9 $mg \cdot kg^{-1}$ resulted in improvements no greater than 1.5% over placebo (Tables 1 and 2). Because some athletic governing bodies have restrictions against large amounts of CAF ingestion (i.e., National Collegiate Athletic Association), but none completely ban CAF use, it is recommended that CAF use not exceed 9 $mg \cdot kg^{-1}$. Performance improvements with CAF ingestion are maximized with amounts up to 6 $mg \cdot kg^{-1}$ and are not further improved with 9 $mg \cdot kg^{-1}$ (10,31). The ergogenicity of CAF up to 6 $mg \cdot kg^{-1}$ has been observed in a variety of settings, but factors such as one's habitual use of CAF may change the dose needed to elicit an ergogenic effect.

Although the recommendations for maximizing CAF's ergogenic properties presented above are also made elsewhere (43,59,60), it is evident that performance improvements with CAF are varied and independent of exercise mode, duration (when >5 minutes), and protocol (Tables 1 and 2). It should be noted that CAF in moderate consumption does not impact hydration status or thermoregulation in exercising individuals (2). Recent reviews conclude that CAF's primary mode of action involves adenosine receptor antagonism in the central nervous system (28,43,52). Caffeine is able to cross the blood-brain barrier and is a powerful antagonist of adenosine receptors in the central nervous system (8). As a result, CAF counteracts the inhibitory effects of adenosine on neuroexcitability, neurotransmitter release, and arousal (20). Because of the potential importance of adenosine receptors on central fatigue, it is important to understand factors that may change or modulate adenosine receptor number or sensitivity. Changes in adenosine receptor number or sensitivity may play a role in the effect that CAF has on exercise performance. Chronic CAF consumption in animal models results in upregulation of the number and an increase in the affinity of adenosine receptors within the central nervous system (11,42). This may result in an increased amount of CAF needed to have the same antagonist activity on the receptors (termed "caffeine habituation"). It is possible that the varied degree of improvements observed between studies (Figure 2) may be attributable to lack of control over subject habituation.

Although there are no known studies examining the effects of CAF habituation on time-trial performance, several studies have examined CAF habituation using other exercise performance protocols. Using a time-to-exhaustion protocol, Van Soeren and Graham (62) measured performance after subjects abstained from CAF for 0, 2, and 4 days. There was a trend for greater improvement with CAF ingestion after abstaining from CAF for 2 and 4 days (vs. 0 days). Similarly, using a time-to-exhaustion protocol, Bell and McLellan (5) showed that improvements in performance were greater for CAF nonusers (< 50 mg CAF per day) vs. users (≥ 300 mg of CAF per day). Therefore, it is possible that CAF habituation may modulate performance improvements with acute CAF ingestion.

It is not known how many days an endurance athlete should abstain from CAF to maximize its ergogenic effects, but animal studies show that increases in adenosine receptor number and affinity are maximized in 7 days (42). Therefore, we recommend that athletes abstain from CAF ingestion for no fewer than 7 days before competition. This should allow for withdrawal symptoms (which may negatively affect performance) to subside and allow sufficient time for adenosine receptor downregulation to occur (42), thus possibly maximizing the ergogenic effects of CAF. Although abstaining from CAF before use in an athletic setting is ideal, some may find it too difficult because of withdrawal symptoms (e.g., headaches, fatigue, lethargy, flulike symptoms) (5,62). Over-the-counter medicine may help alleviate these symptoms, but the interaction of these substances with CAF is unknown. When CAF is habitually consumed, one may improperly conclude that an increase in dosage may be sufficient to elicit an ergogenic effect similar to that experienced by a CAF-naïve individual. Unfortunately, this specific scenario has not been examined in a performance setting. Regardless of habituation level, the ingestion of large amounts of CAF may result in negative side effects (14); therefore, abstaining from CAF before use possibly will give the greatest chance of optimizing the ergogenic effect (5).

In conclusion, there are a number of high-quality research articles that have examined the effects of CAF on time-trial endurance performance. The expected performance improvements with CAF ingestion are varied, but they may be dependent on a number of factors including timing, ingestion mode/vehicle, and subject habituation. Given the available evidence, we recommend that endurance athletes abstain from CAF use at least 7 days before competition.

Acute ingestion should occur no more than 60 minutes before and, if practical, during competition. The amount of CAF commonly shown to improve endurance performance is between 3 and 6 $mg \cdot kg^{-1}$ body mass; these amounts are equally effective when combined with a CE solution or water. Further research should seek to identify specific factors that mediate the large range of improvements commonly observed with CAF ingestion.

Practical Applications

Caffeine is a widely used legal drug that has been shown to improve endurance performance and that, theoretically, could be used before training sessions when high-intensity exercise is desired. The degree of performance improvement is variable and likely influenced by the timing of ingestion, amount ingested, mode of ingestion, and how often an athlete consumes CAF on a daily basis (level of habituation). To maximize performance improvements with CAF ingestion, it is recommended that athletes consume up to 6 $mg \cdot kg^{-1}$ body mass no more than 60 minutes before exercise, but it also may be consumed during exercise. Caffeine seems to be equally effective when ingested in combination with CE solutions (e.g., sports drinks) or other modes of ingestion (e.g., gum), but other substances in caffeinated-coffee may counteract CAF's performance-improving properties. Evidence suggests that consuming CAF every day may dampen the degree of performance improvement observed when CAF naïve. Therefore, we recommend that athletes abstain from CAF no fewer than 7 days before its use in competition. Because some individuals react differently to CAF than others (i.e., CAF sensitive), it is recommended that athletes try CAF while training before using it in competition.

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