SPORTS SCIENCE EXCHANGE

CAFFEINE AND EXERCISE PERFORMANCE

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KEY POINTS

1. Recent, well-controlled studies have established that moderate doses of caffeine ingested 1 h prior to exercise enhance the performance of certain types of endurance exercise in the laboratory. Moderate caffeine doses produce urinary caffeine levels well below the allowable limit, as determined by the International Olympic Committee. The results are specific to well-trained elite or recreational athletes. It is not known if these findings will improve performance in competitions because controlled field studies of the effects of caffeine are lacking.

2. The mechanisms responsible for improved exercise endurance in prolonged exercise remain elusive. A metabolic mechanism appears to contribute early in exercise, when caffeine ingestion increases plasma free-fatty acid concentrations and muscle triglyceride use and spares muscle glycogen. However, it is not clear if increased fat oxidation causes the glycogen sparing in muscle. Increases in plasma epinephrine concentrations usually occur following caffeine ingestion but are not essential for the accompanying metabolic changes. When studying caffeine effects in the human it is difficult to identify the primary source of the "stimulus" because caffeine usually increases epinephrine secretion and is also rapidly metabolized in the liver to three dimethylxanthines (paraxanthine, theophylline and theobromine). The dimethylxanthines can remain in the circulation longer than caffeine and may be metabolic signals in their own right.

3. Caffeine appears to enhance performance during short-term, intense cycling lasting ~5 min in the laboratory and in simulated 1500 m race time. However, positive ergogenic effects of caffeine are much less frequent during sprint exercise lasting less than 90 s and in incremental exercise tests lasting 8-20 min.

4. Potential mechanisms for improving performance during intense exercise lasting 5-20 min include direct effects of caffeine on the central nervous system and/or excitation-contraction coupling and increased anaerobic energy provision in skeletal muscle.

INTRODUCTION

Caffeine is a “controlled or restricted drug” in the athletic world, because urinary levels of greater than 12 µg/mL following competitions are considered illegal by the International Olympic Committee (IOC). However, most athletes that consume caffeine beverages prior to exercise would never approach the illegal limit following a competition. Therefore, caffeine occupies a unique position in the sports world. It is an inherent part of the diet of many athletes although it has no nutritional value and also has the potential to be a "legal" ergogenic aid in many exercise situations. While it is common to equate caffeine with coffee, it should be noted that rarely is coffee the vehicle of administration in research studies. Therefore, it may be misleading to equate the two because coffee contains hundreds of additional chemicals.

In a 1990 Sport Science Exchange article, Wilcox concluded that few well-controlled studies had examined the effects of caffeine on endurance performance and that the results were inconsistent. Since 1990, the research examining caffeine and exercise performance increased and demonstrated the ergogenic effect of caffeine during prolonged endurance exercise (Graham & Spriet, 1991, 1995; Pasman et al., 1995). In addition, investigations examining the effects of caffeine on exercise performance during sprinting (<90 s), intense exercise of short (~5 min) and long duration (~20 min)(Colllomp et al., 1990, 1991; Jackman et al., 1996; MacIntosh & Wright, 1995) have appeared.

There has been general improvement in the quality of the investigations because researchers have attempted to control several factors that may confound the caffeine results. Conlee summarized these factors in a 1991 review article. Three factors relate to the nature of the experimental design, i.e., the exercise modality, the power output, and the caffeine dose, whereas four others relate to the status of the subjects prior to the experiment, i.e., nutritional status, training status, previous caffeine use, and individual variability. An additional factor is the ability to reliably measure exercise performance. This reliability is greater in highly trained subjects than it is in the less well-trained.

Caffeine appears to be taken up by all tissues of the body, making it difficult to independently study the effects of caffeine on the central nervous system, the muscles, and fat tissue in the exercising human. It is also apparent that different mechanisms are probably responsible for performance enhancement in different types of exercise. However, it is important to note that the mechanism(s) may not be entirely due to caffeine. For example, caffeine ingestion usually increases the plasma concentration of epinephrine, a hormone with widespread effects, and the
liver rapidly metabolizes the caffeine, a trimethylxanthine, into three dimethylxan-
thines, i.e., paraxanthine, theophylline, and theobromine. The concentrations of these metabolites increase in the plasma as the caffeine concentration declines, and parax-
thanine and theophylline especially are potential metabolic stimuli. Thus, it is diffi-
cult to resolve which tissues are directly or indirectly affected by which compound.
Due to this uncertainty, when the term "caffeine" is used in this report, the reader
should note that it could be any of the methylxanthines.

THEORIES OF ERGOGENICITY
There are three major theories for the ergogenic effect of caffeine during exercise.
The first theory suggests a direct effect on some portion of the central nervous system
that affects the perception of effort and/or the neural activation of muscle contraction.
The second theory proposes a direct effect of caffeine on skeletal muscle performance.
This may involve ion transport (including Ca⁺ transport) and direct effects on key regu-
latory enzymes, including those controlling glycogen breakdown. Support for
these suggestions is largely derived from in vitro investigations in which high pharma-
cological concentrations of caffeine are used to demonstrate effects. If these "test-
tube" results have any relevance during exercise, the most likely candidates for con-
tributing to an ergogenic effect of caffeine are changes in calcium activity and in the
ability of the muscle to pump potassium from the extracellular fluid to the interior of
the muscle fibers; caffeine levels during exercise are similar to the lowest concentra-
tions of caffeine used in vitro that can affect these processes.
The third theory is the classic or "meta-
bolic" explanation that involves an increase in fat oxidation and a reduction in carbohy-
drate oxidation. In this scheme, caffeine directly enhances the activity of enzymes
that break down fat into fatty acids or caf-
feine increases circulating levels of epi-
ephrine (EPI), which in turn mobilize
free-fatty acids from triglyceride (TG)
stores in fat or muscle tissue. The increased fatty acid availability increases muscle fat
oxidation and reduces carbohydrate oxida-
tion, thereby improving the performance of exercise that becomes exhausting when car-
bohydrate stores reach low levels.
The following sections address the ergogenic potential of caffeine during
varying types of exercise that are catego-
rized according to power output and time to exhaustion or to completion of a race.

CAFFEINE AND ENDURANCE PERFORMANCE
The interest in caffeine as an endurance
ergogenic aid was initially stimulated by
work from Costill's laboratory. They exam-
nined the effect of ingesting 330 mg of caf-
feine 1 h prior to cycling to exhaustion at
80% of maximal oxygen consumption
(VO₂-max) (Costill et al., 1978). The trained
cyclists improved performance from 75 min in the placebo condition to 96 min fol-
lowing caffeine ingestion. A second study demonstrated that 250 mg of caffeine was
associated with a 20% increase in the
amount of work performed in 2 h (Ivy et al., 1979). These studies suggested that utiliza-
tion of fat for energy increased by ~30% in the caffeine trials. A third study examined
exercise muscle metabolism and reported that ingestion of 5 mg of caffeine/kg body
weight spared muscle glycogen and increased the use of muscle TG (Essig et al., 1980). In
the 1980's, few investigations actually tested the ergogenic effects of caf-
feine during endurance exercise; most
examined only how metabolism was
affected by caffeine. Furthermore, conclu-
sions regarding the metabolic effects of caf-
feine were often based on indirect indicators of fat metabolism, i.e., increases in plasma
free-fatty acids (FFA) and/or decreases in the ratio of carbon dioxide production to
oxygen consumption (such decreases indi-
cate that more fat is being utilized for
energy). This work has recently been re-
viewed (Graham et al., 1994; Spriet, 1995;

RECENT STUDIES OF CAFFEINE
EFFECTS ON ENDURANCE
PERFORMANCE AND METABOLISM
Several recent studies have carefully
examined the performance and metabolism
effects of caffeine in well-trained athletes
who are accustomed to exhaustive exercise and race conditions. Most confounding fac-
tors were well controlled, and performance assessments were chosen to simulate com-
petitive conditions. The studies examined the effects of a caffeine dose of 9 mg/kg
body mass on running and cycling time to
exhaustion at 80-85% VO₂-max (Graham &
Spriet, 1991: Spriet et al., 1992), the effects
of varying doses (3-13 mg/kg) of caffeine
on cycling performance (Graham & Spriet,
1995; Pasman et al., 1995) and the effects
of a moderate caffeine dose (5 mg/kg) on
performance of repeated 30 min bouts of
cycling (5 min rest between bouts) at 85-
90% VO₂-max (Trice & Haymes, 1995).
Collectively, this work produced several
important findings. Endurance performance
was improved by ~20-50% compared to the
placebo trial ~20-50% following ingestion of
varying doses of caffeine (3-13 mg/kg) in
elite and recreationally trained athletes who
ran or cycled at ~80-90% VO₂-max. Without
exception, the 3, 5, and 6 mg/kg doses pro-
duced an ergogenic effect with urinary caf-
feine levels that were below the IOC
acceptable limit. Three of four experiments
using a 9 mg/kg dose reported performance
increases, while 6/22 athletes tested in these
studies had urinary caffeine levels at or above 12 µg/mL. Performance was
enhanced with a 13 mg/kg dose, but 6/9
athletes had urinary caffeine levels well
above 12 µg/mL. The side effects of caf-
feine ingestion (dizziness, headache,
insomnia and gastrointestinal distress)
were rare with doses at or below 6 mg/kg,
but prevalent at higher doses (9-13 mg/kg).
Such side effects were associated with
decreased performance in some athletes at
9 mg/kg.
Caffeine generally produced a two-fold
increase in venous plasma EPI at rest and
during exercise and in venous plasma FFA
at rest. The elevated FFA with caffeine
was no longer apparent within 15-20 min of
exercise. At the lowest caffeine dose (3
mg/kg), performance was increased without
significant increases in plasma venous EPI
and FFA. Muscle glycogen utilization was
reduced following caffeine ingestion, but
the "sparing" was limited to the initial 15
min of exercise at ~80% VO₂-max.
There is little information on the perfor-
mane and metabolic effects of caffeine in
recreationally active or untrained subjects
because performances in these groups is dif-
ficult to measure accurately. Chesley et al
(1994) reported a variable glycogen sparing
response to a high caffeine dose (9 mg/kg)
in untrained males. Only 4/8 subjects
demonstrated glycogen sparing during 15
min of cycling at 80-85% VO₂-max. These
results suggest that the metabolic responses
to caffeine ingestion in untrained subjects
are more variable than in aerobically trained
populations.
Recently there was a preliminary report
(Graham et al., 1995) comparing the
effects of caffeine (4.5 mg/kg) in "pure"
tablet form to the same amount of caffeine in a coffee beverage (~two mugs of strong coffee ingested in 10 min). Caffeine as a table-
let resulted in the usual metabolic and perfor-
mance effects, but when ingested as a
beverage there was less of a response in
plasma epinephrine and little or no effect
on performance, even though the plasma
caffeine concentrations were identical.
Presumably the wide variety of com-
pounds in coffee negated the usual ergogenic benefit.

MECHANISMS FOR
IMPROVED ENDURANCE
It seems likely that a metabolic mecha-
nism is part of the explanation for the
improvement in endurance with caffeine,
except at the low caffeine doses for which
this hypothesis has not been fully examined.
The increased FFA at the onset of exercise,
the glycogen sparing in the initial 15 min,
and the report of increased intramuscular
TG use during the first 30 min of exercise
suggest a greater role for fat metabolism
early in exercise following caffeine doses of
5 mg/kg and above. However, these meta-
bolic findings do not preclude other factors
contributing to enhanced endurance perfor-
mance. For example, caffeine appears to
stimulate transport of potassium into inac-
tive tissues, leading to an attenuation of the
rise in plasma potassium concentration
during exercise. It has been postulated that
the lower plasma potassium helps maintain the excitability of the cell membranes in contracting muscles and contributes to caffeine’s ergogenic effect during endurance exercise (Lindering et al., 1993).

It is also noteworthy that EPI does not appear to play a major role in metabolic changes occurring with caffeine ingestion. Performance was enhanced with a caffeine dose of 3 mg/kg without significant increases in plasma EPI and FFA during exercise. In addition, an infusion of EPI that was designed to produce exercise EPI concentrations similar to those induced by caffeine had no effect on plasma FFA or on the rate of glycogen breakdown (Chesley et al., 1995). Also, Van Soeren et al. (1996) gave caffeine to spinal-cord injured subjects and reported increased plasma FFA without changes in EPI. Therefore, the known alterations in muscle metabolism alone cannot presently explain the ergogenic effect of caffeine during endurance exercise in all situations.

CAFFEINE AND PERFORMANCE OF GRADED EXERCISE TESTS

Several studies reported no effect of moderate doses of caffeine ingestion on time to exhaustion and VO2 max during graded exercise protocols lasting 8-20 min (see Dodd et al., 1993) However, two studies from the same laboratory reported prolonged exercise times when high doses of caffeine were given (Finn et al., 1990; McNaughton, 1987). The first study used 10 and 15 mg/kg caffeine doses and reported a small, insignificant increase in performance. However, the control trial always preceded the caffeine trials, leading to the possibility of an order effect. The second study used a 10 mg/kg caffeine dose 3 h prior to cycling exercise and reported an increased time to exhaustion. The subjects completed control, placebo and caffeine trials with the control trial always first, and the remaining two trials randomized. It appears that the high caffeine dose is the most likely factor that separates these positive findings from the studies reporting no effect. Unfortunately, no mechanistic information presently exists to explain the ergogenic effects.

CAFFEINE AND PERFORMANCE OF SHORT-TERM INTENSE EXERCISE

There has been recent interest in the effects of caffeine on performance during short-term intense exercise (~100% VO2 max) lasting ~5 min; near-maximal provision of energy from both aerobic and anaerobic sources is required for such activities.

Collomp et al. (1991) reported that 250 mg of caffeine increased cycle time to exhaustion at 100% VO2 max from 5:20 with placebo to 5:49, although the increase was not significant. A third trial, in which subjects received 250 mg caffeine daily for 5 d also increased exhaustion time non-significantly (5:40). Wiles et al. (1992) reported that drinking coffee containing ~150-200 mg of caffeine improved 1500 m time on a treadmill in well-trained runners by 4.2 s compared to placebo (4:46.0 vs. 4:50.2). In a second protocol subjects drank either coffee or a placebo, ran for 1100 m at a predetermined pace, and then ran 400 m as fast as possible. The average speed of the final 400 was 23.5 km/h with coffee and 22.9 km/h without. Following coffee, all subjects ran faster, and the mean VO2 during the final 400 m was also higher.

A recent study by Jackman et al. (1996) examined the effects of caffeine ingestion (6 mg/kg) on the performance and metabolic responses to repeated bouts of cycling at 100% VO2 max in 14 subjects. Three bouts of exercise were performed with intervening rest periods of 6 min each. The first two cycling bouts at a controlled power output lasted 2 min, and the third continued to exhaustion. Cycle time to exhaustion was improved with caffeine (4.93 ± 0.60 min vs. placebo, 4.12 ± 0.36 min). Muscle and blood lactate measurements throughout the protocol suggested a higher production of lactate in the caffeine trial, even in the initial two bouts when power output was controlled. The net rate of glycogen breakdown was not different during the initial two bouts, and less than 50% of the muscle glycogen store was used in either trial during the protocol. The authors concluded that the ergogenic effect of caffeine during short-term intense exercise was not associated with glycogen sparing and may be caused either by a direct action on the muscle or by altered function of the central nervous system.

In conclusion, the mechanisms contributing to the performance improvement in short-term, intense exercise are not known but may include enhanced anaerobic energy provision, direct effects of caffeine on the transport of ions in muscles, and central nervous system effects on the sensation of effort and/or activation of muscle contraction in appropriate muscle fibers.

CAFFEINE AND SPRINT PERFORMANCE

Sprint performance is defined as fatiguing exercise at power outputs 1.5- to 3-fold greater than that required to elicit VO2 max or maximal efforts in sporting events lasting less than 90 s. The amount of energy derived from anaerobic processes would be ~75-80% of the total in the first 30 s, ~65-70% over 60 s, and ~55-60% over 90 s.

Williams et al. (1988) reported that caffeine ingestion had no effect on maximal power output or muscular endurance during short, maximal bouts of cycling. Collomp et al. (1992) found that ingestion of caffeine at a dose of 5 mg/kg did not increase peak power or total work completed in six subjects performing a 30-s Wingate test. However, the same group later reported that 250 mg of caffeine produced a significant 7% improvement in the maximal power output that could be generated during a series of 6-s sprints at varying force-velocity relationships (Anselme et al., 1992). The same authors also examined the effects of 250 mg of caffeine on two 100-m freestyle swims that were separated by 20 min (Collomp et al., 1990). In well-trained swimmers, the velocity during the first and second swims was improved by 2% and 4%, respectively but performance times were not given.

Therefore, given the present information, it is not possible to conclude whether or not caffeine has an ergogenic effect on sprint performance. The brief and intense nature of sprint exercise makes it very difficult to study and to demonstrate significant effects of caffeine.
studied, including those who routinely
metabolic responses to caffeine is large.
Variability of Caffeine Responses
could produce IOC-illegal amounts of uri-
will have used caffeine in a doping manner.
people caught with illegal levels of caffeine
cise duration and environmental conditions.
important and will be affected by the exer-
ingestion and urine sample collection is
athlete. The time elapsed between caffeine
byproducts that are
excreted are not measured in doping tests.
other factors also affect the amount of caf-
reaches the urine, including body
most of the caffeine is metabolized in the
liver. The caffeine byproducts that are
excreted are not measured in urine samples that would only
approach the urinary caffeine limit. It is not easy to reach the limit by ingesting coffee. A caffeine level above 12 µg/mL suggests that an individual has deliberately taken caffeine in the form of tablets or suppositories in an attempt to improve performance. Not surprisingly, only a few athletes have been caught with illegal caffeine levels during competitions, although formal reports of the frequency of caffeine abuse are rare. One older study reported that 26/775 cyclists had illegal urinary caffeine levels when tested following competition (Delbecke & Debachere, 1984).

Urinary Caffeine and Doping
The use of urinary caffeine levels to determine caffeine abuse in sport has been criticized. Only 0.5-3% of orally ingested caffeine actually reaches the urine because most of the caffeine is metabolized in the liver. The caffeine byproducts that are excreted are not measured in doping tests. Other factors also affect the amount of caffeine that reaches the urine, including body weight, gender, and hydration status of the athlete. The time elapsed between caffeine ingestion and urine sample collection is important and will be affected by the exercise duration and environmental conditions. Sport governing bodies may not regard these concerns as problems because most people caught with illegal levels of caffeine will have used caffeine in a doping manner. However, it is possible that someone who metabolizes caffeine slowly or who excretes 3% of the ingested dose rather than 0.5% could produce IOC-illegal amounts of urinary caffeine following ingestion of a moderate dose of caffeine.

Variability of Caffeine Responses
The variability of performance and metabolic responses to caffeine is large. This appears to be true for all groups studied, including those who routinely ingest small and large amounts of caffeine, users who have withdrawn from caffeine, and non-users. The variability of muscle glycogen sparing following caffeine ingestion is greater in samples of untrained males than in trained males (Chesley et al., 1994; Spriet et al., 1992). Few females have been studied to determine if the variability in response to caffeine ingestion is similar to that in males. Menstrual status needs to be controlled for in these studies because estrogen may affect the half-life of caffeine. Therefore, although mean results in a group of athletes may predict an improved athletic performance, it is impossible to reliably predict that the performance of a given individual will improve.

Habitual Caffeine Consumption
As reviewed by Graham et al. (1994), several recent studies suggest that chronic caffeine use dampens the EPI response to exercise and to caffeine but does not affect indirect markers of fat metabolism during exercise (Bangsbo et al., 1992; Van Soeren et al., 1993). However, these changes do not appear to dampen the ergogenic effect of 9 mg/kg caffeine. Endurance performance increased in all subjects in two studies in which both users and non-users of caffeine were examined; users abstained from caffeine for 48-72 h prior to experiments (Graham & Spriet, 1991; Spriet et al., 1992). However, the performance results were more variable in a subsequent study with more non-users (Graham & Spriet, 1995). In addition, Van Soeren et al. (1993) recently reported that prior caffeine withdrawal for up to 4 d did not affect exercise-induced changes in hormones and metabolism in subjects who acutely ingested caffeine doses of 6 or 9 mg/kg. Performance times in the recreational cyclists riding to exhaustion at 80-85% VO₂max were improved by caffeine, and this was unaffected by 0-4 d of caffeine withdrawal.

Caffeine and High Carbohydrate Diets
It was reported that a high-carbohydrate diet and a pre-race carbohydrate meal negated the expected increase in plasma FFAs following caffeine ingestion during 2 h of exercise at ~75% VO₂max (Weir et al., 1987). These results were interpreted to imply that high-carbohydrate diets would negate the ergogenic effects of caffeine, although endurance performance was not measured. However, a high-carbohydrate diet and a pre-trial carbohydrate meal did not prevent caffeine-induced increases in performance in a number of recent studies using well-trained/recreational runners and cyclists (see Spriet, 1995).

Diuretic Effect of Caffeine
Because caffeine is a diuretic, it has been suggested that caffeine ingestion may lead to poor hydration status prior to and during exercise. However, two studies reported no changes in core temperature, sweat loss, or plasma volume during exercise following caffeine ingestion (Falk et al., 1990; Gordon et al., 1982). A recent report also demonstrated that urine volumes and body hydration status during exercise were unaffected by caffeine ingested in a fluid replacement drink (Wempe et al., 1994).

Ethical Considerations
Since ergogenic effects of caffeine have been reported with doses of 3-6 mg/kg, it is easy for endurance athletes to enhance performance "legally" with caffeine. We suggested on the basis of our work that caffeine should be banned prior to competitions in endurance athletes. This would ensure that no athlete had an unfair advantage on race day but would not prevent caffeine use in training. Athletes would have to abstain from caffeine ~48-72 h prior to competition to achieve this goal. However, in the present climate, what should athletes do? Should they use caffeine in moderate amounts to make sure they are not missing out on a potential beneficial effect, or should they avoid this tactic because it could be considered doping? The former point of view may be popular because caffeine use is prevalent in society, and athletes will not have "illegal" amounts in their urine. Others argue that caffeine use in moderation is a trivial issue; other drugs with more serious side effects require greater attention. Nevertheless, the potential ergogenic effect of caffeine is impressive. On the other hand, discouraging caffeine use counteracts the "win-at-all-costs" mentality and sets the proper example for youth. The Canadian Center for Drug Free Sport reported in 1993 that over 25% of youths aged 11-18 reported using caffeine in the prior year to help them do better in sports.

SUMMARY
Caffeine ingestion (3-13 mg/kg body weight) prior to exercise often increases performance during prolonged endurance cycling and running in a laboratory setting. Caffeine doses below 9 mg/kg generally produce urine caffeine levels below the IOC-allowable limit of 12 mg/mL. Moderate caffeine doses (5-6 mg/kg) also increase short-term intense cycling (~5 min) in the laboratory and decrease swim time for 1500 m (~20 min). These results are generally reported in well-trained elite or recreational athletes, but field studies are lacking to confirm the ergogenic effects of caffeine in the athletic world. The mechanisms for the improved endurance have not been clearly established, but they may involve metabolic, hormonal, or direct effects of caffeine on muscles and/or on the nervous system.
References


