

Caffeine and Athletic Performance: A Mini-Review of Mechanisms and Practical Recommendations

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Abstract

Caffeine is one of the most extensively studied ergogenic aids in the field of athletic performance. The literature is dominated by randomized controlled trials, double-blind crossover studies, systematic reviews, and meta-analyses, which collectively evaluate caffeine's effects on endurance, strength-power outcomes, high-intensity interval exercise, and team-sport performance. This narrative mini-review was based on a targeted literature search of PubMed, Scopus and Web of Science. The most commonly investigated protocol is an acute dose of 3–6 mg·kg⁻¹ administered approximately 30–60 minutes before exercise; this regimen is particularly associated with consistent improvements in endurance performance. Findings for strength and power are more heterogeneous, although pooled analyses generally report small-to-moderate positive effects. Caffeine may also contribute indirectly to performance via enhancements in cognitive alertness, reaction time, and reductions in perceived exertion. However, response magnitude varies substantially between individuals, influenced by factors such as genetic polymorphisms, habitual caffeine use, and individual sensitivity. At higher doses, adverse effects—including anxiety, gastrointestinal disturbances, and sleep disruption—are more frequently observed. Overall, evidence from diverse study designs supports caffeine as an effective ergogenic aid, but its practical application should be tailored to the individual.

Keywords: Athletic Performance, Caffeine, Endurance, Ergogenic Aid, Strength.

Introduction

Caffeine is a methylxanthine alkaloid chemically known as 1,3,7-trimethylxanthine (C₈H₁₀N₄O₂) [1,2]. It is the most widely consumed psychoactive substance worldwide and is commonly ingested via coffee, tea, and energy drinks. In Western countries, approximately 90% of adults consume caffeine regularly. Caffeine is among the most popular and well-researched ergogenic aids used by athletes [3,4]. Since its removal from the World Anti-Doping Agency's (WADA) prohibited list in 2004, caffeine supplementation has become widespread among elite athletes competing internationally, with reported usage rates ranging from 73.8% to 76% [5]. Given its widespread use among athletes, tracing the historical and experimental development of caffeine research helps explain how current evidence evolved.

Early investigations into the effects of caffeine on physical work capacity began in the early 20th century [6], and research on its impact on athletic performance intensified in the 1970s after caffeine was shown to increase time to exhaustion in endurance tests. Today, Although caffeine is a commonly used ergogenic aid, pooled analyses indicate its benefits are generally small-to-moderate and heterogeneous; the magnitude and consistency of effects depend on outcome type, exercise protocol, dose and timing, habitual use, and individual factors such as genetics and body mass. Taken together, these mixed findings highlight the need for a concise synthesis of mechanisms, dosing, and moderators of effect.

This mini-review aims to synthesize current evidence on the ergogenic effects of caffeine supplementation on exercise performance, including mechanisms of action, optimal dosing and timing protocols, and factors that modulate individual responses such as habitual consumption and genetic variability.

Methods

This narrative mini-review was based on a targeted literature search of PubMed, Scopus and Web of Science through which studies addressing caffeine and athletic performance in healthy humans (randomized controlled trials, observational studies, and reviews/meta-analyses) were prioritized, while case reports and non-human studies were excluded.

Pharmacokinetics and Ergogenic Mechanisms of Action

Caffeine is rapidly absorbed from the stomach and small intestine following oral ingestion [7]. After consumption of anhydrous caffeine (capsule form), time to peak plasma concentration typically ranges from 30 to 90 minutes. Caffeine is widely distributed throughout the body and is metabolized in the liver. Its elimination half-life is estimated at 4–6 hours, and the considerable interindividual variability in this parameter—driven by genetic and environmental factors—heightens the importance of supplementation timing [8]. The primary physiological mechanism underlying caffeine's ergogenic effects is its antagonism of adenosine receptors (A₁, A_{2A}, and A_{2B}), due to its structural similarity to adenosine. Adenosine is a central nervous

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system neurotransmitter that promotes fatigue and sedation. By blocking adenosine receptors, caffeine attenuates subjective feelings of fatigue and enhances alertness, perceived energy, and mood. This action contributes to increased neuromuscular excitation. Central antagonism of adenosine receptors is therefore regarded as the primary mechanism explaining caffeine's ergogenic effects during locomotor activities [9]. Although central adenosine-receptor antagonism is widely regarded as the dominant mechanism, additional peripheral mechanisms have been proposed.

Caffeine may theoretically enhance skeletal muscle contractile capacity by increasing the release of calcium ions (Ca^{2+}) from the sarcoplasmic reticulum. However, evidence indicates that the doses required to elicit such direct muscular effects in humans would approach toxic levels [10]. Nevertheless, acute ingestion of a high dose (e.g., 9 mg·kg⁻¹) has been reported to reduce contraction time (T_c) and maximal displacement (D_m) in electrically evoked muscle responses of professional athletes, suggesting a direct positive effect on muscle mechanical activity [11]. In addition to potential direct muscle effects, caffeine also alters whole-body energy metabolism in ways that may support endurance performance.

Caffeine can alter energy metabolism, particularly during endurance exercise. A meta-analysis has shown that acute caffeine intake significantly increases the rate of fat oxidation during submaximal, fasted-state aerobic exercise. This effect is consistent with a reduction in the respiratory exchange ratio (RER). Doses above approximately 3.0 mg·kg⁻¹ are generally required to elicit this metabolic response [12]. The increase in fat oxidation is thought to arise from catecholamine stimulation and/or antagonism of A1 adenosine receptors on adipocytes, thereby promoting lipolysis. However, the practical significance of enhanced fat oxidation—particularly the glycogen-sparing idea—has been increasingly challenged.

Initially, caffeine was hypothesized to enhance endurance by increasing fat utilization and thereby “sparing” muscle glycogen. However, this glycogen-sparing hypothesis has been questioned in recent years and is largely rejected, since glycogen is not a limiting factor during short-duration, high-intensity exercise. Independent of substrate effects, caffeine's central actions also change perception of effort and pain, which can directly affect performance. Caffeine reduces ratings of perceived exertion (RPE) and pain perception via its actions on the central nervous system. This decrease in RPE is an important ergogenic mechanism, allowing athletes to continue exercising for longer or at a higher intensity despite fatigue.

Effects on Exercise Performance

Taken together, the central and peripheral mechanisms described above provide plausible pathways for measurable improvements in many exercise outcomes. Although many studies report ergogenic effects of caffeine across a range of outcomes, pooled analyses indicate these benefits are generally small-to-moderate and heterogeneous. The magnitude and consistency of the effect depend on outcome type, exercise protocol, caffeine dose and timing, habitual caffeine use, and individual factors (e.g., genetics and body mass). Consequently, caffeine should be presented as a potentially useful, but not universally effective, ergogenic aid — its benefit will vary by athlete and context.

More specifically, meta-analyses find the most consistent effects for endurance tasks (time-trial and time-to-exhaustion) and for repeated high-intensity efforts, whereas effects on maximal strength, single maximal sprints, vertical jump height, and throwing performance are typically smaller and more inconsistent across studies. Coaches and

athletes should therefore interpret reported effects in the context of sport-specific demands, study design, and individual response, and consider trialing dose, timing and habituation strategies before applying caffeine routinely in competition.

When consumed acutely—typically at doses of 3–6 mg·kg⁻¹—caffeine improves performance across a wide range of exercise modalities. Caffeine consistently enhances aerobic capacity and endurance performance [13]. In running-based time to exhaustion (TTE) tests, caffeine significantly increases time to exhaustion with a moderate effect size ($g = 0.392$). This benefit has been observed in both trained and recreational runners. Doses of 3–9 mg·kg⁻¹ or 200–300 mg of caffeine have been reported to enhance running performance by meaningfully prolonging endurance and time to exhaustion.

Caffeine intake reduced endurance running time-trial (TT) completion times with a small but significant effect. The ergogenic benefit observed in TTs is smaller than that reported for TTE tests (approximately 0.71% vs 16.97%, respectively). TTs have greater ecological validity because they better simulate real racing conditions. One key mediator of the endurance benefits is lowered perceived exertion, which can allow athletes to sustain higher workloads. Caffeine ingestion reduces ratings of perceived exertion (RPE) during exercise. This perceptual effect allows athletes to feel less fatigued at a given workload or to delay the onset of fatigue. However, the effects of caffeine on RPE in combat sports have been reported as inconsistent [14]. Beyond endurance, investigators have also explored caffeine's effects on strength and muscular endurance during resistance exercise.

Caffeine acts as an ergogenic aid for strength and muscular endurance during resistance exercise. Caffeine ingestion increases one-repetition maximum (1RM) strength (e.g., bench press and squat) as well as isometric and isokinetic strength. These effects are small in magnitude. The minimal effective dose for enhancing resistance-exercise performance is approximately 1.5 mg·kg⁻¹. Caffeine substantially improves muscular endurance by increasing repetitions per set (Cohen's $d = 0.18$ – 2.21). These positive effects have been observed in both single- and multiple-set protocols and across a range of load intensities ($\approx 30\%$, 60% , 70% , and 85% of 1RM). Similarly, caffeine appears to enhance explosive, short-duration tasks by increasing velocity and power output.

Caffeine enhances performance in explosive, short-duration, high-intensity activities. Caffeine ingestion increases velocity and power outputs during resistance exercise; for example, a 3 mg·kg⁻¹ dose has been shown to enhance mean and peak velocity and power in the bench-press. Caffeine enhances Wingate (anaerobic) performance. In Olympic-level boxers, a 6 mg·kg⁻¹ dose of caffeine increased peak power in the Wingate test by 6.27% (Grgic, 2021). Caffeine supplementation can improve single-jump performance (SMD = 0.23) and repeated-jump performance (SMD = 0.51). For example, in elite male volleyball players, a 5 mg·kg⁻¹ dose of caffeine increased counter-movement jump (CMJ) height by 12.2% [15]. Consequently, caffeine's mixed benefits translate well into team-sport contexts that require repeated high-intensity efforts and decision-making.

Caffeine provides benefits in sports characterized by mixed metabolic demands, such as high-intensity interval training (HIIT) and team sports. Caffeine improves performance measures specific to team-sport activities. A meta-analysis in volleyball players demonstrated that caffeine supplementation increased the frequency of positive game actions during simulated match play and improved spike/serve accuracy. Caffeine may be ergogenic in combat sports that require isometric strength, rapid reaction times, and anaerobic

metabolism. In judo, caffeine has been shown to increase the total number of throws during the Special Judo Fitness Test (SJFT) and to enhance hand-grip strength. In taekwondo, ingestion of 5 mg·kg⁻¹ of caffeine has been reported to reduce reaction time. Caffeine may improve agility by reducing completion time on agility tests.

Cognitive and perceptual enhancements are another mechanism through which caffeine can boost sport-specific performance. Cognitive functions-attention, memory, and decision-making-are critical determinants of sports performance. Acute, low-to-moderate doses of caffeine taken before and/or during exercise enhance attention, alertness, perceived energy, and mood. Meta-analyses have demonstrated that caffeine supplementation significantly improves attention accuracy and response speed.

Individual Differences, Optimal Protocols, and Safety Considerations

The most commonly used and recommended dose is 3–6 mg·kg⁻¹ body mass, administered in capsule form 30–60 minutes before exercise [16]. Because caffeine capsules typically reach peak plasma concentration within 30–90 minutes, taking capsules ~60 minutes pre-exercise is generally recommended [17]. Formulation and timing matter: delivery methods that accelerate absorption can change the practical timing of ingestion. Because caffeinated chewing gum and gels are absorbed more rapidly, they can enhance resistance-exercise performance even when consumed as little as 10 minutes before exercise. Interindividual variability in caffeine responses has been linked to polymorphisms in genes that regulate caffeine metabolism (e.g., CYP1A2) and genes related to adenosine receptors (e.g., ADORA2A). Identifying these genetic differences is important for informing personalized nutrition strategies. Genetic variability interacts with behavioral factors, so both genotype and habitual intake influence optimal dosing strategies.

Contrary to common belief, the majority of current research indicates that habitual (regular) caffeine consumption does not abolish the acute ergogenic benefits of caffeine. However, it has been suggested that highly habituated consumers may require higher doses (e.g., 6–9 mg·kg⁻¹) to achieve performance-enhancing effects. In addition to biological moderators, psychological factors such as expectancy can also shape the observed ergogenic response. A small portion of caffeine's ergogenic effects may be placebo-driven. An individual's belief that they have ingested caffeine can markedly enhance performance, likely via expectancy-behavior interactions and changes in arousal.

The adverse effects of caffeine are dose-dependent. High doses (9–13 mg·kg⁻¹) can increase the likelihood of adverse symptoms such as gastrointestinal disturbances, nervousness, headache, palpitations, and tremors. Caffeine negatively affects sleep quality, particularly when consumed close to bedtime, by reducing total sleep time (TST) and sleep efficiency (SE) [18]. There is no definitive evidence that caffeine ingestion during exercise in hot environments adversely affects thermoregulation or impairs performance; however, some studies have suggested that caffeinated non-alcoholic beverages may exacerbate post-exercise kidney injury under high-temperature conditions.

Conclusion and Clinical Implications

Caffeine supplementation has been extensively investigated across exercise-science and biomedical disciplines; current evidence supports its role as an ergogenic and cognitive enhancer. In the context of physical performance, caffeine has been consistently shown to improve endurance, resistance exercise, and both aerobic and anaerobic activities [19]. For example, acute caffeine intake has been reported to enhance Wingate performance [20] and to increase per-

formance in resistance training-particularly during moderate-to-high repetition sets-and, in some cases, to raise maximal strength (1RM) in a dose-dependent manner. Acute caffeine supplementation has also been reported to enhance performance in combat sports, and meta-analytic evidence indicates a significant increase in positive game actions under simulated match conditions in team sports such as volleyball. Mechanistically, a direct effect of a 9 mg·kg⁻¹ dose of caffeine on the mechanical activity of electrically stimulated skeletal muscle has been observed in professional athletes, with reductions in contraction time (Tc) and maximal displacement (Dm) - findings that are indicative of increased muscle tone. Cognitively, caffeine exerts meaningful benefits on attention, accuracy, and speed, and low-to-moderate acute doses can improve self-reported energy, mood, simple reaction time, and perceived fatigue. These effects are largely attributed to caffeine's principal mechanism of adenosine-receptor antagonism. Despite the central physiological role of caffeine, the placebo effect is also influential in sports settings: expectancy alone-believing one has ingested caffeine-can significantly enhance performance, underscoring the contribution of psychological and neurobiological interactions to performance outcomes. Clinically, caffeine's stimulatory action on the central nervous system, especially via blockade of A2A adenosine receptors, is important for sleep-wake regulation [21,22] and has yielded vital therapeutic benefits in neonatology: caffeine citrate has been shown to reduce the risk of apnea and to lower the incidence of complications such as bronchopulmonary dysplasia and patent ductus arteriosus in preterm infants [23].

However, caffeine's effects on sleep regulatory systems are dose- and timing-dependent. For instance, a high dose (e.g., 400 mg) taken 4 hours before bedtime was associated with an approximate 50.6-minute reduction in total sleep time (TST), and habitual caffeine consumption has been shown to delay REM sleep onset and impair sleep quality [24,25]. Overall, while the optimal performance-enhancing dose and timing are generally in the range of 3–6 mg·kg⁻¹, interindividual differences (e.g., genetic background, habitual intake) can modulate response magnitude (Delleli et al., 2022; Oliphant et al., 2024). In conclusion, caffeine produces scientifically supported and consistent improvements across a broad array of physical and cognitive parameters, but its use should be managed carefully with consideration for its effects on sleep quality and dose-dependent adverse responses.

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