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Ergogenic Properties of Caffeine in the Diet of Athletes

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Abstract

Caffeine is one of the most widely consumed and extensively studied ergogenic aids in both amateur and professional sports. Its prevalence spans athletes across a range of disciplines. While some athletes regard caffeine as beneficial for athletic performance, others incorporate it into their daily routine. In competitive sports, where every detail of preparation can be essential, caffeine supplementation is frequently employed to enhance physical performance, cognitive function, and training capacity.

This review summarizes current scientific evidence regarding the pharmacokinetics, mechanisms, effects, and safety of caffeine use in athletic populations. Biochemically, caffeine is a naturally occurring methylxanthine with rapid absorption, high bioavailability, and predictable hepatic cytochrome P450 1A2 mediated metabolism.

Its ergogenic effects are attributed to non-selective antagonism of central adenosine receptors, which increases nervous system excitability, reduces perception of effort and pain, and enhances neuromuscular, cognitive, and psychomotor functions. Evidence-based recommendations indicate that low to moderate doses of caffeine, administered before or during exercise, are effective for most athletes, while smaller repeated doses are advantageous during prolonged events requiring sustained performance.

Caffeine is generally considered safe within recommended limits; however, individual variability in dietary habits, genetic factors, and sensitivity necessitates personalized supplementation strategies.

Overall, caffeine is a safe and effective ergogenic aid when used appropriately, with optimal outcomes achieved through individualized protocols tailored to specific sports and competition contexts.

Key words: caffeine, athletes, ergogenic aids, supplementation, diet

Content:

Introduction:

Athletes in various sport disciplines, such as combat and endurance sports, must perform at different exercise intensities, placing demands on multiple physiological capacities. In competitive settings where success and defeat are separated by minimal margins, even small factors may determine the outcome. Consequently, elite athletes often implement nutritional ergogenic aids (NEAs) into their training and competition strategies to enhance both training capacity and athletic performance[1]. NEAs are substances used to support training outcomes or competitive performance in specific disciplines, aiming to avoid harmful effects on the individual[2], while also modulating inflammatory response, reducing oxidative stress, and adapting signaling pathways[3]. Given the rising worldwide consumption of NEAs, regulatory bodies such as the World Anti-Doping Agency (WADA) and the Australian Institute of Sport have proposed classifications of sports supplements, grouping them into different categories[2]. Of these, Group A includes supplements with effects supported by scientific evidence, permitted in specific situations according to best-practice guidelines, and are further divided into three subgroups: sports foods, medical supplements, and performance supplements[1].

Among NEAs, beta-alanine, creatine, caffeine, nitrates, and protein are considered the most efficient and beneficial for athletes. All of them improve performance, but caffeine is the most widely used and well-researched ergogenic aid. It can be consumed in a capsule or added to beverages. Caffeine is common in pre-workout stages and energy drinks[4].

It may be beneficial in endurance, aerobic, and combat sports. It is believed to increase muscular strength, stimulate neural excitability, and enhance cognitive function, such as attention and reaction time[5,6]. Caffeine intake has been associated with maintaining neurological health, reducing the risk of neurodegenerative diseases, managing type 2 diabetes, preventing cancer through antioxidant activity, and modulating reactive oxygen species (ROS) production. Excessive ROS can disrupt cellular damage repair mechanisms, leading to intracellular deoxyribonucleic acid mutations, irreversible damage to proteins and lipids, and the development of various diseases. Clinical studies have shown an inverse association between dietary caffeine intake and Parkinson's disease risk[7].

Although caffeine has been widely used, it remains a subject of study. Therefore, the aim of this review is to summarize and critically evaluate the current scientific evidence on the efficacy, mechanisms of action, and practical applications of caffeine supplementation for athletic performance.

1. Caffeine - general characteristics

1.1. Natural occurrence and dietary sources of caffeine

Caffeine (1,3,7-trimethylcanthine or 3,7-dihydro-1,3,7-trimethyl-1H-purine-2,6-dione or C8H10N4O2) is a plant-derived purine alkaloid. It is present in more than 6 different plants, such as *Coffea arabica*, *Coffea canephora*, *Theobroma cacao*, *Cola acuminatam*, *Camellia sinensis*[7,8]. It is the most commonly used substance due to its presence in beverages and foods. According to data published by the European Food Safety Authority, the average daily consumption of caffeine in young adults (18–65 years old) is 37–319 milligrams (mg)[9]. Some resources claim that average caffeine consumption from all sources reaches 76 mg per person per day; another one reported that in 2020–2021, coffee consumption was around 166.63 million 60 kilograms (kg) bags worldwide[7]. Dietary sources of caffeine are coffee and cocoa beans, tea leaves, guarana berries, and kola nuts. Caffeine is produced either by extraction from these sources or by synthetic procedures (e.g., methylation of various xanthines and theophylline)[7,9].

1.2. Pharmacokinetics and bioavailability of caffeine

After oral ingestion, the small intestine absorbs almost all of the caffeine within approximately 45 minutes (min), with minimal first-pass metabolism[8]. Caffeine peak plasma concentrations vary between 15 and 120 min and are dependent on different factors, such as gastric emptying, intestinal pH (potential of hydrogen), and food intake[7,8].

When caffeine is absorbed, it is quickly distributed throughout tissues and fluids. At this point, it is highly bioavailable, able to cross the lipid barrier and the blood-brain barrier[7,10]. After absorption, caffeine binds to proteins: about 10-30% associates reversibly with albumin and other plasma proteins, while the rest remains freely diffusible[8]. Caffeine does not accumulate in any specific tissue; its distribution volume ranges from 0.5 to 0.75 litters (L) per kg[8]. Drinking a typical cup of black coffee (0.4–2.5 mg/kg) results in peak plasma caffeine concentrations of approximately 0.25–2 mg/L. Higher peak concentrations are reached with 5–8 mg/kg doses after 30 to 75 min[8].

The organ responsible for caffeine metabolism is the liver, especially via cytochrome P450 enzymes in human liver microsomes, with cytochrome P450 1A2 (CYP1A2) responsible for 80% of its biotransformation; moreover, caffeine itself may increase CYP1A2 activity[7,10]. CYP1A2 is responsible for the demethylation of caffeine to 3,7-dimethylxanthine (theobromine) and 1,3-dimethylxanthine (theophylline). These can be demethylated by CYP1A2 and then undergo further reactions to form substances that can lead to the formation of uric acid and xanthine derivatives, which are excreted primarily in the urine[7].

The metabolic half-life of caffeine is usually 3 to 5 hours. Nevertheless, there have been cases of its removal within 7 hours, depending on individual characteristics such as age, sex, pregnancy status, smoking, liver function, and use of other medications[7,10]. Because caffeine is rapidly distributed and excreted, its levels do not accumulate unless it is consumed consistently[8].

Renal excretion is the main route of caffeine elimination, with approximately 0.5–5% excreted unchanged in urine. Small amounts can also be detected in bile, saliva, semen, and breast milk[7]. Because of its rapid absorption, high oral bioavailability, and predictable pharmacokinetics, caffeine allows for rapid maintenance of plasma concentrations, which is important for therapeutic and functional uses[8].

2. Mechanisms of the ergogenic effects of caffeine

The ergogenic properties of caffeine result from several central and peripheral mechanisms. These mechanisms affect neuromuscular function, metabolism, perception of exertion, and cognitive performance. They act synergistically and may vary depending on the type of exercise, intensity, and individual characteristics.

2.1. Antagonism of Adenosine Receptors in the Central Nervous System

The main mechanism underlying the ergogenic effect of caffeine is its role as a non-selective antagonist of adenosine A_1 and A_2A receptors in the central nervous system (CNS).

The accumulation of adenosine during prolonged wakefulness and physical exertion promotes fatigue, vasodilation, and decreased nerve excitability. By blocking adenosine receptors, caffeine reduces inhibitory neurotransmission. This leads to increased neuronal activity, increased alertness, and reduced perception of effort and pain[10].

Adenosine receptor antagonism also increases the release of excitatory neurotransmitters such as dopamine, norepinephrine, and acetylcholine. These substances are associated with improved mood, alertness, motivation, and reaction time—factors that are particularly important in high-intensity and high-skill sports[11].

2.2. Neuromuscular Function and Motor Unit Recruitment

Caffeine has been shown to enhance neuromuscular transmission and motor unit recruitment, thereby increasing force production and muscular endurance. This enhancement is likely mediated by increased central nervous system drive to skeletal muscles and improved excitation–contraction coupling. Experimental studies indicate that caffeine increases calcium (Ca^{2+}) release from the sarcoplasmic reticulum, thereby improving muscle fiber contractility, especially during repeated or sustained contractions[12,13].

These neuromuscular effects are more pronounced during submaximal and endurance-type efforts compared to single maximal contractions. This distinction may account for the variability observed in strength-based outcomes.

2.3. Metabolic Effects and Substrate Utilization

Caffeine influences energy metabolism by stimulating catecholamine release. This enhances lipolysis and increases circulating free fatty acids. Early hypotheses suggested that caffeine improves endurance performance by preserving muscle glycogen. This preservation is associated with greater fat oxidation. While this mechanism may contribute modestly under specific conditions, current evidence suggests that central nervous system effects play a more dominant role in performance enhancement[14,15].

Based on these metabolic effects, caffeine may improve metabolic efficiency during prolonged exercise sessions by maintaining plasma glucose levels and delaying hypoglycemia, particularly during endurance events lasting longer than 90 minutes[16].

2.4. Perception of Effort, Pain, and Fatigue

In addition to its metabolic effects, caffeine is recognized for its ergogenic properties, particularly its capacity to reduce the rating of perceived exertion and diminish pain associated with physical activity. Caffeine modulates pain perception by affecting central adenosine pathways and interacting with endogenous opioid systems. As a result, athletes can maintain higher workloads at the same subjective intensities, which enhances endurance and performance during repeated exercise sessions[3,12].

3. Effects of caffeine on physical performance and exercise capacity

3.1. Physical Performance

Caffeine supplementation has been shown to enhance endurance performance in activities such as cycling, running, rowing, and cross-country skiing. Meta-analyses indicate that caffeine doses of 3–6 mg/kg are associated with performance improvements of approximately 2–4% in both time-trial and time-to-exhaustion protocols[14,15].

The performance benefits are primarily attributed to reductions in perceived exertion, increased alertness, and improved pacing strategies, rather than solely to metabolic effects.

Caffeine demonstrates efficacy in activities involving intermittent and repeated sprints, such as team sports including soccer, rugby, and basketball, as well as combat sports. Supplementation with caffeine is linked to enhanced sprint performance, greater jump height, increased total work output, and accelerated decision-making speed[3,15].

In combat sports, caffeine can improve reaction time, increase alertness, and improve technical performance, particularly during later rounds when fatigue impairs performance.

The effects of caffeine on maximal strength are less consistent than its impact on endurance outcomes. Some strong evidence indicates that caffeine enhances muscular endurance, increases total volume lifted, and improves resistance to fatigue during multi-set protocols, but this effect is less evident in one-repetition protocols[11,13].

These findings suggest that caffeine is particularly beneficial during training sessions focused on hypertrophy or high-volume resistance work. The demonstrated utility of both strength and endurance naturally leads to considering how caffeine may also affect cognitive and psychomotor attributes in athletic contexts.

3.2. Cognitive Performance

Caffeine consistently improves cognitive aspects connected to athletic performance. It enhances attention, vigilance, reaction time, and decision-making accuracy. These effects are particularly important in sports that demand rapid information processing and tactical execution under fatigue[7,11].

4. Practical recommendations for caffeine use in sport performance

4.1. Dose and timing

Data from literature reviews indicate that currently, caffeine supplementation in low-to-moderate doses (~3-6 mg/kg) 30-60 min before physical activity is effective in enhancing various types of performance and in most athletes[12,14]. In smaller doses (1-3 mg/kg), they can also effectively support endurance, especially cognitive endurance. At the same time, they are safer because they are associated with fewer side effects[17,18]. In addition, it has been proven that consuming caffeine in larger doses (>9 mg/kg) does not improve performance[11].

4.2. Type of exercise

Although caffeine supplementation is used in many sports, it is particularly beneficial in endurance exercise, intermittent team sports, and repeated-sprint activities[15,17]. However, findings for maximal strength and single explosive efforts are inconsistent, with some protocols reporting improvements in muscular endurance and total training volume have been reported in resistance exercise protocols Grgic J et al.[18,19].

4.3. Form of administration

Caffeine may be administered in various forms, including capsules, coffee, energy drinks, gels, and chewing gum[14]. The best form for precise supplementation is caffeinated chewing gum, which allows faster absorption via the buccal mucosa and is particularly helpful when caffeine is consumed shortly before or during exercise[20]. Coffee is another good source of caffeine. However, its caffeine content can make it difficult to measure out accurately[21].

4.4. Use during prolonged events

In endurance sports or events lasting several hours, administering small, repeated caffeine doses (1–2 mg/kg) during activity helps maintain plasma caffeine concentrations and delay the onset of fatigue[15,17,22]. This approach has demonstrated efficacy in cycling, running, and ultra-endurance disciplines.

4.5. Individual variability

Individual variability in response to caffeine supplementation is determined by factors such as habitual caffeine consumption, genetic polymorphisms (especially CYP1A2), sex, and training status[11,23]. Therefore, caffeine intake strategies should be evaluated during training sessions rather than implemented for the first time in competition. Current evidence does not consistently support complete caffeine withdrawal before competition as a strategy to enhance ergogenic effects[11].

4.6. Sleep, Recovery, and Competition Scheduling

Given caffeine's elimination half-life of 3 to 7 hours, consumption during late-afternoon or evening competitions may impair sleep quality and impede recovery[24]. For athletes participating in multi-day or evening events, caffeine supplementation should be restricted to small doses, administered earlier in the day, or avoided entirely, depending on individual sensitivity[24,25].

5. Safety of caffeine

Caffeine is generally considered safe within recommended limits. Safety varies with dose, individual sensitivity, and timing.

5.1. Acute Side Effects

Most athletes tolerate moderate caffeine doses (≤6 mg/kg) without major side effects. Higher doses may cause anxiety, gastrointestinal discomfort, tachycardia, tremors, or insomnia. These adverse effects can offset performance benefits, especially for those sensitive to anxiety or unaccustomed to caffeine[26].

5.2. Chronic Use and Dependence

Regular caffeine use leads to physiological tolerance, primarily through the upregulation of adenosine receptors and adaptive changes within both the central and peripheral nervous systems. These changes reduce caffeine’s stimulating and performance-boosting effects over time[27]. Tolerance is demonstrated by attenuated cardiovascular, metabolic, and personal responses to caffeine after regular use[28]. As a result, people who use caffeine regularly may see a smaller performance boost than those who rarely use it, even with the same dose[29].

Abrupt cessation of caffeine intake among habitual users frequently precipitates a withdrawal syndrome, which is characterized by headache, fatigue, decreased alertness, irritability, depressed mood, and impaired concentration. This syndrome generally emerges within 12 to 24 hours after cessation, peaks within 1 to 2 days, and may persist for up to 7 days[30]. If not properly managed, withdrawal symptoms can adversely impact training quality and competitive readiness.

Despite these physiological adaptations, current evidence does not support complete caffeine withdrawal prior to competition as an effective method for restoring or enhancing ergogenic efficacy. Multiple controlled trials and systematic reviews demonstrate that acute caffeine ingestion continues to provide performance benefits in habitual users, even without a withdrawal period, indicating that certain ergogenic effects persist despite tolerance[28]. Although habitual use may diminish some subjective effects, it does not consistently eliminate improvements in endurance, power output, or cognitive performance following acute supplementation.

Accordingly, individualized caffeine strategies that consider habitual intake, genetic variations in caffeine metabolism such as CYP1A2 genotype, and specific competition requirements are recommended in place of uniform withdrawal protocols[11]. Adjusting caffeine intake to align with an athlete’s habitual consumption may optimize efficacy and reduce withdrawal-related disruptions to training.

5.3. Cardiovascular and Regulatory Considerations

Moderate caffeine consumption is generally considered safe for cardiovascular health in athletes. Acute caffeine intake may temporarily elevate heart rate and blood pressure by stimulating the sympathetic nervous system and antagonizing adenosine receptors. These physiological responses are generally transient and less pronounced in athletes who regularly consume caffeine[7]. Large epidemiological studies and meta-analyses show that regular caffeine consumption is not associated with an increased risk of cardiovascular disease and may even correlate with a reduced incidence of coronary heart disease, stroke, and heart failure[31,32]. This suggests that there are no long-term harmful effects on the cardiovascular system in athletic populations. In trained individuals, caffeine doses commonly used for ergogenic purposes (≤6 mg/kg) have not been associated with an increased risk of arrhythmia or adverse cardiovascular events. However, caution is needed for athletes with pre-existing cardiovascular conditions or heightened sensitivity to stimulants[11].

Caffeine is not prohibited by WADA, although it remains on the Monitoring Program because of its widespread use and potential for misuse[33].

6. Conclusions

In summary, caffeine is one of the most common supplements in the diet of athletes. Its pharmacokinetics and metabolism make it easy to dose. Although it is available in many forms, it is recommended to use it in the form of chewing gum before physical activity. Due to the fact that caffeine is a non-selective antagonist of adenosine A_1 and A_2A receptors, it leads to increased central nervous system stimulation, reduced inhibitory effects of adenosine, and increased alertness and concentration. In addition, caffeine affects neuromuscular transmission and motor unit recruitment. That affects activation of motor units, and improved power generation capacity, especially in conditions of fatigue.

Caffeine also affects the perception of effort, pain, and fatigue, making the effort subjectively feel less intense, increasing the pain tolerance threshold, and delaying the onset of fatigue, which allows for higher intensity exercise to be maintained for longer periods of time. When it comes to physical exertion, caffeine is recommended for all types of activities, from endurance sports to high-intensity and intermittent exercises. Due to its effect on cognitive and psychomotor performance, caffeine improves reaction time, decision-making ability, selective attention, and precision of movements, especially in conditions of physical and mental fatigue.

This effect translates into better neuromuscular coordination, greater technical accuracy, and faster response to external stimuli, which is important in team sports, technical sports, and sports requiring a high level of concentration. There are some doubts about its effect on strength and resistance exercise, which requires further, well-controlled studies taking into account the level of training, caffeine dose, habituation, and the nature of the exercise performed in order to clearly determine the scale and mechanisms of potential ergogenic benefits.

Caffeine is an effective ergogenic aid, enhancing efficiency and performance when administered in moderate doses with appropriate timing and individualized strategies. Optimal benefits are achieved when supplementation protocols are tailored to the athlete's physiological characteristics, sport-specific requirements, and competition context.

Disclosure

Supplementary Materials

There are no supplementary data connected with this article.

Author Contributions

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All authors have read and agreed to the published version of the manuscript.

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Declaration of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors used Grammarly for the purpose of improving language and readability. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the substantive content of the publication.

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