



International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Scholarly Publisher
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ARTICLE TITLE

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CAFFEINE IN ATHLETIC PERFORMANCE

DOI

[https://doi.org/10.31435/ijitss.4\(48\).2025.4016](https://doi.org/10.31435/ijitss.4(48).2025.4016)

RECEIVED

03 October 2025

ACCEPTED

16 December 2025

PUBLISHED

24 December 2025

LICENSE



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A CRITICAL REVIEW OF THE ERGOGENIC POTENTIAL OF CAFFEINE IN ATHLETIC PERFORMANCE

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ABSTRACT

Purpose: This review provides a comprehensive synthesis of current evidence regarding the ergogenic properties of caffeine supplementation by critically evaluating its impact on exercise performance, fatigue attenuation, and post-exercise recovery.

Methodology: A systematic review of scientific literature published from 2015 was performed to examine the influence of caffeine on physical performance. The analysis includes randomized controlled trials, meta-analyses, and observational studies across a range of sports disciplines and population groups.

Findings: Caffeine supplementation, particularly at doses of 3–6 mg/kg body mass taken approximately one hour before exercise, significantly enhances both aerobic and anaerobic performance. Meta-analyses confirm improvements in endurance, power output, muscular strength, and fatigue resistance across various athletic populations. Caffeine also reduces delayed-onset muscle soreness and may aid recovery, though its impact on heart rate variability post-exercise appears negligible. Individual responses vary based on sex, habitual intake, training status, and genetic factors.

Conclusions: Caffeine is an effective and well-supported ergogenic aid for improving multiple dimensions of physical performance. Optimal benefits are achieved with moderate doses, while excessive intake may increase adverse effects without additional performance gains. Personalization of caffeine strategies based on individual characteristics is recommended to maximize efficacy and safety.

KEYWORDS

Caffeine, Exercise Performance, Endurance, Fatigue, Exercise Recovery, Anaerobic Exercise, Aerobic Exercise

CITATION

Wojciech Gawęda, Wiktoria Łobodzińska, Maciej Ficek, Justyna Adamczyk, Zuzanna Hamouta, Szymon Cholewiński. (2025). A Critical Review of the Ergogenic Potential of Caffeine in Athletic Performance. *International Journal of Innovative Technologies in Social Science*. 4(48). doi: 10.31435/ijitss.4(48).2025.4016

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1. Introduction

Caffeine is one of the most widely consumed psychoactive substances globally and has long been recognized for its potential ergogenic properties. Its use in sports and exercise science has prompted extensive research into its physiological effects on human performance. As a central nervous system stimulant, caffeine influences alertness, pain perception, and perceived exertion during physical activity.

Caffeine exerts its ergogenic effects primarily through antagonism of adenosine receptors in the central nervous system. By blocking adenosine, a neuromodulator that promotes relaxation and fatigue caffeine increases neuronal excitability, reduces the perception of effort, and enhances alertness and concentration. Additionally, caffeine stimulates the release of catecholamines such as adrenaline, which may contribute to improved energy availability and exercise capacity. On a muscular level, caffeine facilitates calcium release within muscle cells, potentially enhancing muscle fiber recruitment and contractility.

The aim of this article is to comprehensively review current scientific literature regarding the impact of caffeine supplementation on physical performance, with a particular focus on its effects in both aerobic and anaerobic disciplines. This review also examines caffeine's role in reducing muscle fatigue and soreness, its influence on post-exercise recovery, and the variability of its effects based on individual factors such as sex, training status, habitual intake, and genetic predisposition. This review aims to provide a comprehensive evaluation of caffeine as a natural supplement for enhancing athletic performance, highlighting both its benefits and potential limitations.

2. Methodology

This review was conducted using a comprehensive search of the scientific literature across PubMed, Scopus and Google Scholar, focusing on publications from 2017 to 2025. The inclusion criteria targeted randomized controlled trials, systematic reviews and meta-analyses that examined the effects of caffeine supplementation on physical performance outcomes. Specific areas of interest included aerobic and anaerobic endurance, muscular strength, neuromuscular fatigue, post-exercise recovery, and delayed-onset muscle soreness (DOMS). Studies involving both trained athletes and recreationally active individuals were included to capture a broad perspective on caffeine's ergogenic potential across diverse athletic populations. Key parameters such as caffeine dosage, timing of administration, mode of delivery, and exercise type were carefully considered. In addition, individual variability factors such as sex, habitual caffeine consumption, training status, and genetic predisposition were analyzed where data allowed. The selected studies were critically appraised for methodological quality and relevance. Outcomes were synthesized thematically to identify consistent patterns in the ergogenic effects of caffeine and to evaluate the practical applications of supplementation strategies. Safety, tolerability, and potential performance-enhancing benefits were reviewed to support evidence-based recommendations for caffeine use in sport and exercise contexts.

3. Mechanism of action

Caffeine, a commonly consumed psychoactive compound of the methylxanthine class, is widely ingested through beverages and pharmaceutical products. Its global prevalence and well-documented effects on alertness, fatigue attenuation and exercise performance have led to extensive investigation within the context of athletic and clinical populations. Elucidating its pharmacological mechanisms is essential for understanding its impact on human physiology and for evaluating its potential role as an ergogenic aid and adjunctive therapy in sports and exercise-related settings:

- **Adenosine Receptor Antagonism:** Caffeine exerts its primary physiological effects through competitive antagonism of adenosine receptors, particularly the A₁ and A_{2A} subtypes within the central nervous system. Adenosine normally acts as an inhibitory neuromodulator, promoting sedation and suppressing arousal. By blocking these receptors, caffeine mitigates adenosine's depressant effects, resulting in heightened wakefulness, enhanced alertness, and reduced perception of fatigue. Furthermore, this antagonism facilitates the increased synaptic availability of excitatory neurotransmitters, including dopamine, norepinephrine, acetylcholine, and serotonin, thereby contributing to improved cognitive performance and mood regulation (1,2).

- **Calcium Mobilization and Muscle Contractility:** Caffeine enhances calcium release from sarcoplasmic reticulum in skeletal muscle by sensitizing ryanodine receptors (RyR). This causes an extra release of Ca^{2+} into muscle fibers beyond the normal stimulation. The resulting increase in cytosolic calcium improves excitation-contraction coupling, leading to enhanced muscle contractility and force output (1). This effect contributes to improved neuromuscular performance, especially under conditions of fatigue.

- **Phosphodiesterase Inhibition:** At higher systemic concentrations, caffeine acts as a phosphodiesterase (PDE) inhibitor, particularly targeting PDE4. Inhibition of PDE leads to increased intracellular levels of cyclic adenosine monophosphate (cAMP), thereby enhancing signal transduction related to energy metabolism. This results in augmented lipolysis, glycogenolysis, and thermogenic responses during physical exertion, thereby improving endurance performance (1).

- **Regulation of Myoglobin Expression:** Recent findings suggest that caffeine can upregulate myoglobin expression in skeletal muscle through activation of the cAMP-dependent protein kinase A (PKA) signaling pathway. Myoglobin plays a vital role in intracellular oxygen transport and storage, and its increased expression may facilitate enhanced oxidative metabolism during prolonged exercise (1,3). These mechanisms implicate caffeine as a potential modulator of aerobic performance, likely mediated through molecular adaptations in skeletal muscle tissue.

4. Review of Studies on the Impact of Caffeine on Physical Performance

Aerobic Endurance

A comprehensive meta-analysis examining endurance running performance demonstrated that caffeine intake led to a significant improvement in the time to exhaustion. This benefit, with a medium effect size, was observed in both recreational ($g = 0.469$; 95% CI = 0.185 to 0.754; $p = 0.001$) and trained runners ($g = 0.344$; 95% CI = 0.122 to 0.566; $p = 0.002$), suggesting that caffeine can help individuals maintain aerobic activity for a longer duration, irrespective of their training level (4). In specific populations, such as professional male kickboxers, even low doses of caffeine supplementation (around 3mg/kg of body weight) have been shown to increase the time to exhaustion, highlighting the potential for caffeine to enhance endurance across various aerobic activities (5). In addition to its effect on time to exhaustion, the aforementioned meta-analysis on running also revealed a small, but statistically significant reduction in the time taken to complete endurance running time trials with caffeine intake ($g = 0.392$; 95% CI = 0.214 to 0.571; $p < 0.001$) (4). Another meta-analysis that focused on cyclist found that moderate doses of caffeine, specifically in the range of 4 to 6 mg/kg of body weight, significantly improved cycling time trial performance. This improvement was evidenced by both a decrease in the overall completion time (SMD Time = -0.55, 95% CI = -0.84 to -0.26; $p < 0.01$) and an increase in the mean power output sustained during trial (SMD MPO = 0.44; 95% CI = 0.09 to 0.79; $p < 0.05$) (6). The observation of higher optimal dosage for cycling compared to general range for running suggests that the ideal caffeine intake might be activity-specific, possibly due to differences in the physiological demands of each sport.

Anaerobic Endurance

In separate study focused on the effects of caffeine during real or simulated competition in intermittent sports revealed that caffeine ingestion led to an increase in both the frequency and the success rate of high-intensity sport-specific actions. It included sprints, body impacts, accelerations and decelerations suggesting that caffeine can enhance performance in sports characterized by repeated bursts of intense activity (11). Furthermore meta-analyses have consistently demonstrated that caffeine supplementation results in a significant improvement in both muscle strength (SMD = 0.18, 95 % CI: 0.14, 0.21; $p < 0.001$) and endurance (SMD = 0.30, 95 % CI 0.21, 0.38; $p < 0.001$). These effects appear to be more pronounced when consumed at dosages of 5 mg/kg of body weight or higher (12). Specific studies have also shown that acute caffeine ingestion, at dosage of around 6 mg/kg of body weight, can improve peak (0.80 ± 0.29 W/Kg, $p=0.01$) and mean power output (0.39 ± 0.02 W/Kg, $p=0.01$) in anaerobic tests such as Wingate test, particularly in young athletes (14). In sports like volleyball, which demand explosive power for actions such as jumping, caffeine has been found to enhance vertical jump height, peak power and the velocity at which peak power is achieved (15). These collective findings underscore caffeine's role as an effective ergogenic aid for enhancing various aspects of anaerobic performance, including the ability to generate strength and power, as well as the capacity to sustain high-intensity efforts. It is important to note that the impact of caffeine on muscle strength and power might not be uniform across all muscle groups and could vary depending on the specific type of anaerobic activity being performed (16). Moreover, individual factors such as an athlete's training status, their habitual caffeine intake and even their genetic predispositions can influence how they respond to caffeine supplementation in the context of anaerobic performance (15).

Reduction of Muscle Fatigue

Meta-analyses have indicated that caffeine can lead to improvements in physiological markers associated with the ability of the nervous system to activate muscles, such as voluntary activation (SMD = 1.46; 95% CI: 0.13 to 2.79; $p < 0.00001$), potentiated twitch response (SMD = 1.11, 95% CI: -1.61 to 3.84; $p < 0.00001$) and M-wave amplitude (SMD = 1.10, 95% CI: -0.21 to 2.41; $p < 0.00001$) (17). This findings suggest that caffeine can enhance the efficiency of the communication between the nervous system and the muscles, potentially delaying the onset of fatigue at the muscular level (18). Additionally, caffeine's ability to increase the release of calcium ions from the sarcoplasmic reticulum within muscle cells can contribute to enhanced muscle contractility, which might also play a role in delaying peripheral fatigue. From a metabolic perspective, caffeine's influence on substrate utilization, particularly the increased reliance on fat oxidation during exercise, can help to conserve muscle glycogen stores (4). This shift in fuel economy allows the body to rely more on its abundant fat reserves, potentially extending the duration of high-intensity effort that can be sustained. However, the effectiveness of caffeine in reducing fatigue might depend on the specific type and intensity of exercise, as seen in a study by Matsumura et al. (2024) where no significant ergogenic or fatigue-reducing effects were observed during very high-intensity sprint interval exercise with significant muscle pain (19). This suggests that under conditions of extreme physiological stress, the benefits of caffeine in mitigating fatigue might be less pronounced or could be overridden by other dominant factors such as intense pain or the rapid depletion of critical energy substrates.

Reduction of Muscle Soreness

Research suggests that caffeine can help reduce muscle soreness, particularly delayed-onset muscle soreness (DOMS). A meta-analysis by Maliji et al. (2021) found that caffeine supplementation can be effective in reducing DOMS, particularly when assessed around 48 hours post-exercise (SMD = -0.92; 95% CI: -2.20 to 0.36) (20). Randomized controlled trial published in 2019 investigated the effects of caffeine ingestion (6 mg/kg) on muscle performance and DOMS in elite college athletes following exercise-induced muscle damage. The study found that caffeine helped restore impaired maximal voluntary isometric contractions (MVIC) in both male and female athletes (10.2% overall and 7.2% post-supplementation, both $p < 0.05$) (18). Also in a study involving professional male kickboxers, Saremi et al. (2024) examined the effects of low to moderate doses of caffeine (3 mg/kg and 6 mg/kg) on performance and muscle soreness. They reported that the higher caffeine dose (6 mg/kg) significantly reduced muscle soreness 2 hours post-exercise compared to both the lower dose (3 mg/kg) and a placebo ($P < 0.05$) (5).

Improvement of Recovery

The role of caffeine in post-exercise recovery is an area of ongoing investigation with studies examining its effects on various physiological markers and recovery processes. Meta-analyses examining the influence of caffeine intake on heart rate variability (HRV) during the post-exercise recovery period have generally found no significant effects. For instance, a meta-analysis by Sargent et al. (2024) reported a standardized mean difference (SMD) of -0.03 (95% CI -0.265 to 0.197, $p=0.77$) for RMSSD and an SMD of -0.061 (95% CI -0.272 to 0.150, $p=0.57$) for the HF index, indicating no substantial variations between placebo and caffeine conditions in these HRV indices post-exercise (13). Similarly, another study from 2022 did not observe a significant impact of caffeine intake on HRV recovery after exercise, with a total 95% confidence interval for RMSSD ranging from -0.45 to 0.29 ($p = 0.67$) and for HF index ranging from -0.34 to 0.30 ($p = 0.22$) (21). It's important to consider that caffeine might negatively impact sleep quality if consumed too close to bedtime, which is crucial for recovery.

Influence of Individual Variables on Caffeine's Effects

Systematic reviews have indicated that caffeine generally provides similar ergogenic benefits for aerobic performance and the fatigue index in both male and female athletes (10). However, for anaerobic performance, some evidence suggests that men might experience a greater enhancement in power output and sprint performance compared to women when given the same dose of caffeine. (10). Moreover, a 2019 study provides further evidence that male athletes experienced a greater reduction in DOMS (21.5%, $p < 0.05$) compared to female athletes (4.6%, $p < 0.05$) after caffeine consumption during MVIC when affected by muscle damage (18). Research has also revealed that habitual caffeine consumption can lead to the development of tolerance, potentially diminishing the ergogenic effects over time in both trained and untrained individuals ($P < 0.05$). Interestingly, short-term caffeine withdrawal might help to restore its effectiveness in habitual consumers ($P < 0.05$) (9).

Optimal Caffeine Supplementation Strategies

The majority of research indicates that a caffeine dosage of 3 to 6 mg/kg of body mass, ingested approximately 60 minutes before exercise, is generally effective for enhancing performance across a wide range of activities (7). Lower doses, around 3 mg/kg, might be sufficient for improving agility and potentially reducing muscle soreness (15). It is worth noting that very high doses of caffeine are generally discouraged (above 6 mg/kg) as they are associated with an increased risk of side effects without providing additional performance benefits (7). Evidence from the studies indicates that habitual daily caffeine intake up to 400 mg for healthy adults is generally considered safe and might even offer some health benefits (8).

Conclusions

The current evidence supports caffeine as a well-established ergogenic aid that enhances both aerobic and anaerobic performance. Mechanistically, caffeine exerts its effects through central nervous system stimulation via adenosine receptor antagonism, enhanced calcium mobilization in muscle tissue, and increased intracellular cAMP levels. These processes contribute to improved endurance, strength, and delayed onset of fatigue. Moderate doses of 3–6 mg/kg body weight, typically taken about one hour before exercise, appear effective and safe for most individuals. Additionally, caffeine shows promise in reducing delayed-onset muscle soreness and improving neuromuscular activation, although its role in recovery—especially regarding heart rate variability and sleep quality—remains inconclusive. Individual responses may vary based on habitual caffeine use, sex, and genetic factors. Overall, caffeine represents a versatile and practical performance-enhancing compound when used judiciously within evidence-based dosing strategies.

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All authors have read and agreed with published version of manuscript.

Funding Statement: The study did not receive special funding.

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