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Brewed for Performance: Caffeine's Impact on Nutrition, Endurance and Strength in Sports

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ABSTRACT

Caffeine is one of the most widely consumed and studied stimulants worldwide with a long history in athletics as a performance enhancer. Although listed as a stimulant in the World Anti-Doping Agency's (WADA's) 2024 Monitoring Program, its use is not prohibited.

Individual responses to caffeine vary widely due to factors like genetics, age, and lifestyle habits, such as smoking and diet.

This paper examines caffeine's multifaced role in human metabolism, with an emphasis on athletes' training (endurance and strength) and post-exercise recovery.

Our comprehensive review of literature indicates that caffeine typically ingested one hour before exercise in doses around 3-6 mg/kg raises metabolic rate, increases free fatty acids mobilization, extends time to exhaustion in running and cycling, improves maximal voluntary contraction and enhances high-speed muscular activity with low-load movements. It also blocks pain perception. These findings highlight caffeine's role in endurance and strength sports. However, due to inconsistencies, further research is needed to develop exercise-specific protocols considering dose, timing, and training status.

Caffeine aids recovery by reducing delayed - onset muscle soreness, improving glycogen resynthesis, and reducing fatigue. However, late consumption may affect sleep, requiring careful timing and dosage adjustments. Moreover, potential side and positive effects of caffeine ingestion need to be considered.

KEYWORDS: Caffeine, Endurance, Strength, Sport, Post-Exercise Recovery

INTRODUCTION

Caffeine, or 1,3,7-trimethylxanthine, is one of the most widely consumed and studied stimulants worldwide [1]. Found in various foods and drinks, especially coffee and tea, it has been culturally significant for centuries due to its stimulating properties and habitual use [2]. Despite its high consumption, caffeine use is generally habitual rather than addictive, with about 90% of adults globally incorporating it into their diets to boost alertness and reduce fatigue, benefits especially valued by shift workers, drivers, and athletes [3,4].

Caffeine has a long history in athletics as a performance enhancer. Research on its effects in sports began over a century ago, gaining attention in the 1970s when studies suggested it could improve endurance [5]. Though caffeine was temporarily regulated as a doping substance in 1984, it was removed from the banned list in 2004, with moderate use remaining typical among athletes due to limited extra benefit from higher doses [6].

Individual responses to caffeine vary widely due to factors like genetics, age, and lifestyle habits, such as smoking and diet [7]. As a xanthine compound, caffeine interacts with molecular targets in the body, including adenosine receptors, which enhances alertness, reduces fatigue, and supports cognitive and physical performance [8]. In vascular tissue, it can promote vasodilation or, in some cases, vasoconstriction, depending on the context [9].

In the brain, caffeine blocks adenosine receptors, thereby increasing levels of neurotransmitters like dopamine and norepinephrine, which heightens focus, mood, and motivation, key for athletic performance [10–12]. Its ergogenic effects—particularly for endurance and muscle function—are linked to complex cellular interactions and vary with exercise type and individual factors, emphasizing caffeine's notable role in enhancing athletic performance. The summary of caffeine's impact on human body is presented in Figure 1.

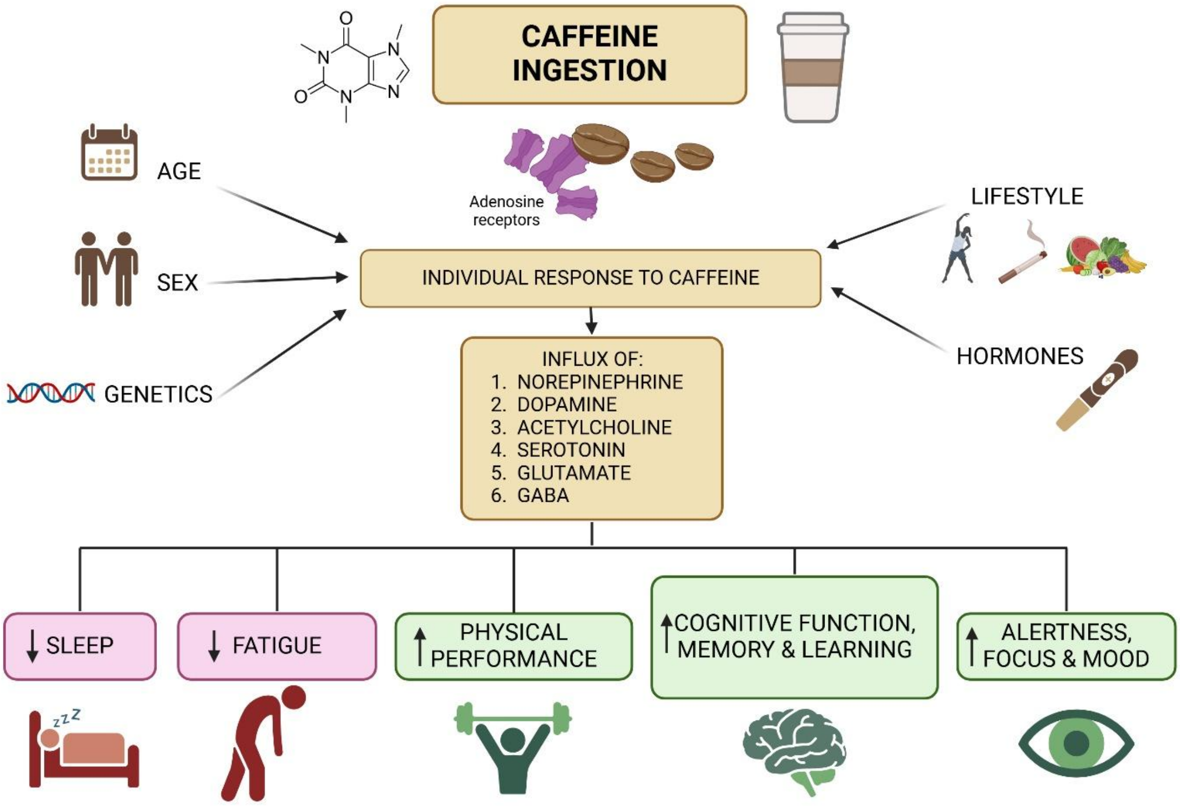


Figure 1: Caffeine's impact on human body after ingestion, mechanism that underly these effects and factors that contribute to individual response to caffeine.

CHAPTER 1: Caffeine and Endurance Performance

1) Mechanisms of Caffeine's Impact on Endurance:

The body's energy source mobilization varies based on exercise intensity. During maximal exertion, muscle adenosine triphosphate (ATP) and creatine phosphate are depleted within seconds. For intense exercise lasting a few minutes, glycogen serves as the main fuel, though its availability is limited by lactate buildup and cellular acidosis. When exercise extends beyond two minutes, energy comes from both glucose and fatty acid (FA) oxidation, with fat use increasing as duration lengthens or intensity decreases. In prolonged exercise, such as a 100 km run, glycogen and triglyceride stores in muscles may deplete entirely. Under such conditions, energy is predominantly sourced from liver glycogen and fat tissue triglycerides, with amino acid oxidation providing a minor contribution (5-10%). Caffeine enhances free fatty acid (FFA) release from fat stores, increasing FA availability for oxidation in muscles, which in turn affects energy management and output during exercise [13].

Acheson et al. investigated caffeine's effects on metabolism in normal and obese individuals. They found that 8 mg/kg of caffeine significantly raised metabolic rate in normal-weight subjects, resulting in a 16% increase in energy expenditure over three hours post-ingestion. While glucose, insulin, and carbohydrate oxidation remained stable, plasma FFA nearly doubled, boosting fat oxidation during the test's final hour. Trials using coffee (4 mg/kg caffeine) showed similar metabolic increases in both normal and obese groups, but significant fat oxidation only occurred in the normal-weight group. Thus, caffeine or coffee elevates metabolic rate across body types but promotes higher fat oxidation in normal-weight individuals [14].

According to Hawley et al. [15], caffeine increases plasma FA in many studies [16–18], though this doesn't always translate to enhanced fat oxidation or reduced glycogen usage, possibly due to the already elevated exercise-induced FA levels. Caffeine also reduces skeletal muscle malonyl coenzyme A (malonyl-CoA) [19], which may explain why it increases FA oxidation at rest but not during exercise when muscle malonyl-CoA is naturally low due to reduced insulin. Caffeine may also indirectly counteract its own lipolytic effect during exercise by stimulating liver glycogen breakdown, increasing lactate, which can inhibit fat breakdown [20,21].

2) Caffeine's Effect on Aerobic Endurance:

Ingesting caffeine before prolonged exercise delays fatigue, though the mechanisms remain unclear [22]. Several studies show caffeine (3–9 mg/kg) extends time to exhaustion by 20-50% during intense exercise [23,24]. Initially, it was suggested that caffeine's effect stemmed from increased FFA, promoting fat metabolism and sparing glycogen [23]. However, Davis et al. argued this glycogen-sparing theory lacks strong support. Additionally, while caffeine elevates plasma epinephrine, this effect might actually hinder endurance due to epinephrine's role in glycogen breakdown and lactate production [25].

Costill et al. studied caffeine's effect on metabolism and performance in cyclists, finding that caffeine enhanced endurance time and lipid metabolism compared to a placebo. Participants rated exercise under caffeine as easier, suggesting caffeine's positive effects on lipolysis and neural transmission [23].

Studies by Graham and Spriet demonstrated that high caffeine doses improve endurance by increasing exercise time to exhaustion, both in running and cycling [26]. Black et al. explored caffeine's impact on perceived exertion, strength, and endurance performance, finding that it enhanced leg muscle strength and reduced perceived effort during cycling, suggesting that caffeine's benefits on endurance may be linked more to strength and motor-unit recruitment than pain or perceived effort reduction [27].

A systematic review by Shen et al. identified a linear relationship between endurance event duration and caffeine's effect on performance, with longer events benefitting more from caffeine ingestion [11].

While many studies measure caffeine's effect through time-to-exhaustion tests, Ganio et al. recommend time-trial tests for more consistent and applicable results. Their review found that moderate caffeine intake (3-6 mg/kg) enhances endurance performance, though responses vary significantly across individuals [28].

3) Practical Applications in Endurance Sports:

Caffeine has demonstrated ergogenic effects across various dosing protocols. Studies suggest that doses around 3-6 mg/kg taken one hour before exercise optimize endurance performance [29]. Graham and Spriet noted that both low (3 mg/kg) and moderate (6 mg/kg) caffeine doses enhance endurance, while higher doses (9 mg/kg) add no further benefit [16]. Meta-analyses by Southward et al. and Higgins et al. confirm small yet significant performance improvements with moderate caffeine doses [30,31]. Desbrow et al. found that doubling a 3 mg/kg dose did not increase performance, suggesting athletes should stick to moderate pre-exercise doses to maximize benefit while minimizing side effects [29]. Animal studies show that adenosine receptors increase in number and sensitivity within seven days.

Ganio et al. suggest avoiding caffeine for at least seven days before use to maximize its performance benefits [28].

Caffeine appears equally effective whether ingested before or during exercise, with a slightly greater performance boost when taken at both times [28]. Davenport et al. showed that caffeine was most effective when taken about an hour before exercise, though more research is needed to refine timing and dose protocols [4,32].

CHAPTER 2: Caffeine and Strength Performance

1) Mechanisms Behind Caffeine's Impact on Strength:

Research on caffeine's effects on strength is limited but suggests that caffeine may directly influence muscle excitation-contraction coupling and motor unit recruitment, independently of its effects on metabolic efficiency [33–35]. Most of these studies focus on maximal isometric strength, with limited investigation into caffeine's impact on neuromuscular function during dynamic contractions at varying speeds [36]. Caffeine may enhance strength by directly affecting muscle, such as by maintaining electrolyte balance or boosting calcium release in the sarcoplasmic reticulum, or by acting on the central nervous system (CNS) to increase motor unit recruitment. The literature on caffeine's effect on muscle strength is mixed, with some reviews claiming benefits and others finding no effect. Warren et al.'s meta-analysis concluded that caffeine improves both maximal voluntary contraction (MVC) strength and muscular endurance, particularly in knee extensors, though not in other muscle groups such as the forearm or knee flexors, and mainly in open-endurance tests [37].

In Bazzucchi et al.'s controlled trial, subjects showed enhanced torque–angular velocity curves after caffeine supplementation, with an 8.7% increase in muscle fiber conduction velocity (CV). This finding supports the hypothesis that caffeine may improve motor unit recruitment during short-duration, maximal dynamic contractions [36].

Caffeine has also been found to stimulate 5'-adenosine monophosphate-activated protein kinase (AMPK) in resting skeletal muscle, which plays a role in glucose transport independent of insulin during muscle contractions. Tsuda et al. found that caffeine and muscle contraction together stimulate AMPK activity, promoting energy consumption and possibly reducing muscle fatigue [38]. However, research on caffeine's effects on muscle fatigue resistance during short, intense activities has shown varied results. While early studies reported no effect of caffeine on peak power output or fatigue rates during high-intensity exercise [39,40], later research found improvements in muscle performance and increased activity during maximal contractions [41,42]. Caffeine may enhance endurance in short-duration intense exercise due to its direct action on muscles or neural processes, rather than glycogen sparing [41]. This suggests an ergogenic benefit for resistance exercises, including strength, endurance, and power [43]. These inconsistent findings underscore the need for further research on caffeine's effects on muscle fatigue resistance in short, high-intensity activities.

2) Caffeine's Effect on Anaerobic Strength:

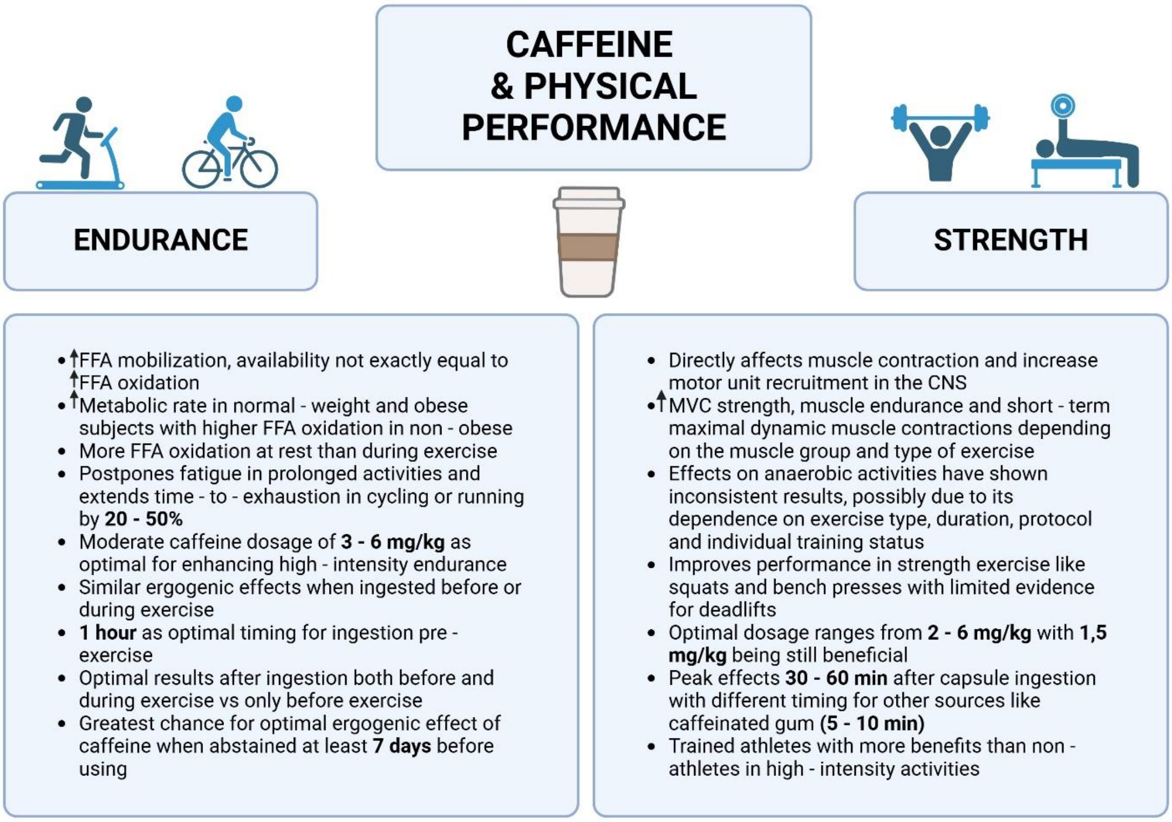
Despite years of research on caffeine's influence on anaerobic power output and muscle contraction force, results remain conflicting. Some studies indicate that caffeine (5-6 mg/kg) significantly increases peak anaerobic power output and blood lactate levels during intense cycling sprints [44], while other studies show no significant effect under anaerobic conditions [45]. Similarly, older studies found no impact of caffeine on power output or muscle contraction in the Wingate test [46,47], yet Grgic's meta-analysis suggests that caffeine may indeed enhance anaerobic power output [48].

The inconsistency may be due to variations in exercise type, protocol, dosing, and subjects' training status. Moderate doses (~3 mg/kg) may enhance performance in endurance, team, and high-intensity sports. [4,49,50]. Astorino and Roberson's review suggests caffeine can enhance performance in high-intensity, short-term exercises like sprinting and weightlifting, particularly in elite athletes who do not regularly consume caffeine [50]. Caffeine seems to improve maximum performance in exercises lasting less than five minutes, though results are mixed and mechanisms require further clarification [51]. Caffeine's ergogenic effect in anaerobic exercise seems to vary by exercise duration, test protocol, and participant training status. In exercises under 30 seconds, caffeine benefits may be restricted to athletes, whereas longer efforts (60-180 seconds) show broader benefits [52]. Beck et al. found that a caffeine supplement improved upper-body strength but had no effect on leg endurance or power [53]. Further studies indicate caffeine's small benefit for strength-trained men, especially heavy caffeine users [54]. Wilk et al. found out that acute caffeine intake did not significantly impact power output or bar velocity in habitual caffeine users. Their study aimed to evaluate the effects of caffeine doses of 3, 6, and 9 mg/kg body mass (b.m.) on these performance metrics during bench press exercises. Participants, who were regular caffeine consumers, completed three sets of five repetitions at 50% of their one-repetition maximum (1RM) in each session. Performance was measured under four conditions: a placebo (PLAC) and three caffeine doses (CAF-3, CAF-6, CAF-9) [55].

3) Practical Applications in Strength Sports:

Lower caffeine doses (2–3 mg/kg) can enhance resistance exercise performance comparably to higher doses (6 mg/kg), while even smaller amounts (~1.5 mg/kg) may still offer benefits [43]. In studies on strength athletes who regularly consume caffeine, high doses (9 and 11 mg/kg) did not significantly enhance performance during bench press repetitions [56]. Caffeine appears to improve performance in strength exercises like squats and bench presses, though evidence is limited for deadlifts. The optimal dose likely ranges from 2 to 6 mg/kg, with peak effects occurring 30-60 minutes after capsule ingestion; however, caffeinated gum may work within 5-10 minutes [43,57].

In shorter events, a single caffeine dose may be sufficient, while in longer events, repeated small doses might maintain performance between rounds. During training, using caffeine only before the most intense sessions may help maintain its effectiveness for competitions, as tolerance from daily caffeine use could reduce its effects [43,57]. High doses (~9 mg/kg) may be necessary for heavy-load activities, while lower doses (~3 mg/kg) can enhance high-speed, low-load movements with fewer side effects [58]. Trained athletes may experience caffeine's benefits more than non-athletes, especially in high-intensity activities like resistance training and peak power tests [50]. Caffeine tolerance, defined as a diminished physiological response following repeated exposure, is attributed to upregulated adenosine receptor activity and attenuated β-adrenergic signaling. In individuals with low habitual caffeine consumption, lower doses are typically well-tolerated; however, complete tolerance can develop within 5–6 days of consistent moderate intake. For nonhabitual users, a gradual escalation of caffeine intake over 3–4 days may optimize its ergogenic effects during high-intensity training while also enhancing cognitive focus and attenuating exercise-induced discomfort. A gradual approach starting with low doses (1-2 mg/kg) and increasing over a few days is recommended to avoid side effects. Tailoring caffeine intake to individual characteristics, including body



size, training status, and tolerance, may optimize performance gains [59]. Figure_2 shows the most important findings and practical applications from Chapter 1 & 2.

Figure_2: Summary of the most important findings of caffeine's effects on physical performance, practical applications and usage recommendations divided into endurance and strength sports.

CHAPTER 3: Caffeine's Effects on Recovery and Adaptation

1) Caffeine's Role in Post-Exercise Recovery

Carbohydrates are the primary energy source during exercise, significantly influencing endurance performance [60]. Muscle glycogen stores are only partially replenished hours post-exercise, highlighting the need for effective nutritional strategies to optimize glycogen synthesis, particularly during the early recovery phase (0–4 hours) when synthesis rates are elevated [61]. High-glycemic-index carbohydrates (≥1.0 g/kg) consumed immediately after exercise can restore glycogen within 24 hours [1], but athletes engaging in multiple daily sessions require faster replenishment [62]. Adequate exogenous carbohydrate (CHO) intake enhances glycogen repletion following glycogen-depleting exercise [63].

Recent studies indicate that coingesting caffeine with CHOs post-exercise may accelerate glycogen synthesis and improve high-intensity interval performance compared to CHOs alone [64]. Pedersen et al. [65] observed increased glycogen resynthesis with caffeine-CHO coingestion in real-world conditions. Loureiro et al. [66] reported improved glycogen recovery during a 4-hour recovery period when coffee with sweetened milk was consumed, compared to sweetened milk alone—a strategy beneficial for athletes with short recovery windows (<4 hours). However, Beelen et al. [67] found no significant differences in glycogen recovery between CHO-only and CHO-caffeine treatments.

Coffee's bioactive components (caffeine, cafestol, caffeic acid) may contribute to glycogen restoration [68]. Mellbye et al. [69] demonstrated that cafestol and caffeic acid enhanced insulin secretion and glucose uptake in muscle cells, supporting insulin-independent glycogen recovery. Caffeine also activates AMPK catalytic α subunit (AMPKα) Thr^{172} and acetyl-CoA carboxylase (ACC) Ser^{79} phosphorylation, promoting glucose transport in skeletal muscle [70]. Similarly, caffeic acid enhances AMPK signaling, boosting glucose uptake in rat muscle [38].

Early recovery may involve caffeine-stimulated glycogen synthase activity, increasing glycogen accumulation [66]. However, Battram et al. [71] found decreased glycogen synthase activity after a 5-hour recovery with caffeine intake. M.V. Esteca et al. [72] revealed caffeine's role in mitochondrial quality control during muscle regeneration, enhancing AMPKα phosphorylation and mitochondrial capacity. Parkin deficiency appeared to amplify caffeine's ergogenic effects by promoting mitochondrial growth.

Caffeine may also mitigate delayed-onset muscle soreness (DOMS), a marker of exercise-induced muscle damage (EIMD), which typically occurs 24–72 hours post-exercise [73]. Maridakis et al. [74] observed reduced pain perception 24–48 hours post-exercise with caffeine supplementation. Another study reported reduced DOMS two days after exhaustive resistance exercises in young men [75]. These findings suggest caffeine effectively alleviates DOMS-related discomfort, especially after single-joint exercises.

Acute caffeine supplementation (e.g., 6 mg/kg) has been shown to reduce DOMS and improve maximal voluntary isometric contraction (MVIC) performance, with male athletes benefiting more than females [76]. This effect likely arises from adenosine receptor inhibition in the CNS, reducing pain perception and fatigue [25]. Enhanced glycolytic flux and lactate accumulation may also prolong performance [25]. Additionally, caffeine lowers serum potassium levels and raises circulating glucose and lactate post-exercise, potentially explaining improvements in recovery metrics and MVIC [76].

Caffeine reduces pain perception during moderate- and high-intensity cycling and alleviates DOMS under EIMD conditions [73,75,77]. For instance, Cortez et al. [78] found that caffeine decreased fatigue during Taekwondo performance compared to placebo after strenuous exercise [79].

By reducing DOMS and associated soreness, caffeine may support more frequent training sessions, ultimately enhancing performance outcomes compared to placebo conditions [75].

2) Caffeine and Sleep Disruption: Impact on Recovery

Athletes often require more high-quality sleep than non-athletes to recover effectively from training and competition stressors [80,81]. Insufficient sleep compromises recovery, increases illness and injury risks, and negatively affects cognition, pain perception, and sport-specific skills like reaction times and accuracy, potentially impacting performance outcomes [82–86]. Despite its importance, many athletes report poor sleep, particularly before competitions, with 66% experiencing worsened sleep quality (SQ) due to factors such as noise, light, anxiety, and nervousness [87–89].

Caffeine, though ergogenic, adversely affects sleep metrics, including efficiency, latency, and total duration, especially when consumed close to bedtime [90,91]. Sleep is critical for nervous system and metabolic recovery [92,93], and caffeine use before late competitions may impair SQ and subsequent recovery, hindering next-day performance. Studies consistently show caffeine’s negative impacts on sleep duration and quality, particularly when consumed in the evening (2–6 mg/kg), 45–75 minutes before exercise [90,94–100].

Reduced total sleep time (−1.2 to −2.8 hours) [90,94,96], lower sleep efficiency (−5.8% to −15.4%) [90,94,95], and increased sleep latency (+7.8 to +40.9 minutes) [90,95] were reported in several studies. Wake after sleep onset increased (+22.9 to +33.2 minutes), with one study observing an average of 5.3 additional awakenings post-caffeine [90,95]. Subjective measures, such as perceived SQ, latency, and insomnia prevalence, also worsened with caffeine use [95,97–99]. Endurance athletes consuming ≤1.5 cups/day reported significantly better SQ than those with higher intake [100], aligning with findings that 400 mg of caffeine six hours before bed disrupts SQ in adults [101].

Caffeine's half-life of 4–6 hours [102] underscores the need for careful timing and dosage. Super Rugby players consuming ~2 mg/kg caffeine before evening games reported reduced sleep duration, lower efficiency, and longer latency [103]. Similarly, Salinero et al. [104] linked 3 mg/kg caffeine energy drinks to higher insomnia rates in endurance athletes. Daily intake exceeding 1.5 cups (>150 mg caffeine) correlated with poorer SQ, while reduced consumption improved SQ, particularly in women, who experience prolonged caffeine effects compared to men [100,105].

To optimize performance, athletes may benefit from intermittent caffeine dishabituation, as abstinence for over four days enhances its ergogenic effects [56,106]. Recovery strategies after nighttime caffeine intake include additional sleep opportunities, avoiding early morning sessions, and adjusting travel schedules to extend sleep [107]. Limiting caffeine to ≤1.5 cups/day may mitigate SQ issues, particularly in women [104,105].

Although caffeine does not significantly affect creatine kinase (CK), a recovery marker, its potential to impair recovery via sleep disturbances warrants caution [90,108–110]. Despite recommendations to limit use, 75–90% of professional athletes consume caffeine before or during training and competition [6,111,112].

CHAPTER 4: Potential Side vs Positive effects of Caffeine Consumption

1) Adverse Effects of Caffeine

Caffeine consumption, particularly at higher doses (6–9 mg/kg), has been associated with adverse effects such as anxiety, nausea, and vomiting [113]. Lower doses (e.g., 3 mg/kg) demonstrate fewer side effects, as shown in one study [103]. Common adverse effects among athletes include increased urine output, tachycardia, palpitations, and anxiety [104]. The CAF-9 trial reported side effects in 0–69% of participants, with symptoms like tachycardia, gastrointestinal issues, and heightened vigor more frequent in CAF than PLAC groups. Higher doses (CAF-11) further increased adverse effect rates to 0–88% [56]. Pasman et al. [114] similarly found more frequent adverse effects with doses of 9–13 mg/kg. Hypersensitive individuals may experience side effects at even lower doses [58]. Excessive caffeine intake (>2000 mg/day) poses severe health risks, including hypertension, arrhythmias, seizures, and death [1,115].

Individual variability in caffeine response is significant. Some individuals are more prone to anxiogenic effects [116] or sleep disturbances [117]. Those with anxiety or panic disorders often avoid caffeine, as it may exacerbate symptoms [118–121]. Gender differences in caffeine effects have also been noted. One study found adverse effects in 30% of men and 54% of women following low (3 mg/kg) or moderate (6 mg/kg) doses, with anxiety and nervousness over three times more frequent in women. While more than 50% of men reported positive effects, only 20% of women did so, potentially due to differences in body composition, such as free fat mass [122]. Caffeine distribution depends on free body mass [123], with women's typically lower free fat mass and higher fat mass resulting in greater caffeine plasma concentrations and increased side effect likelihood [124,125]. Chronic caffeine use has also been linked to an elevated risk of cardiovascular diseases in some studies [126,127].

2) Positive Effects of Caffeine

Caffeine, beyond its performance-enhancing effects, offers additional health benefits potentially advantageous for athletic outcomes. Structurally resembling adenosine, caffeine inhibits adenosine's action on the CNS, reducing pain transmission and providing analgesic effects for conditions like chronic headaches, migraines, and postoperative pain [128]. Acute caffeine intake also enhances endothelium-dependent vasodilation by boosting nitric oxide production, improving blood flow and oxygen delivery during exercise [129].

Caffeine's cognitive benefits include improved memory, cognition [130,131], and insulin sensitivity, lowering type-2 diabetes risk [132]. It heightens perception and vigor [133,134], while studies in mice suggest it protects against diet-induced non-alcoholic fatty liver disease (NAFLD) through Interleukin-6/Signal Transducer and Activator of Transcription 3 (IL-6/STAT3) - mediated lipid catabolism, highlighting therapeutic potential for NAFLD [135]. Moderate caffeine intake (~55.44 mg/kg, four to five 200 mL coffee cups daily) has been shown to inhibit osteoclastogenesis and promote osteogenesis, potentially aiding osteoporosis management. However, higher doses (>110.88 mg/kg, eight to ten cups daily) may disrupt bone homeostasis and weaken bone strength [136].

Chronic caffeine use in animal models increases sensitivity to amphetamines, cocaine, and nicotine while modifying dopamine receptor dynamics [137]. Though caffeine does not directly bind to dopamine receptors, it influences dopaminergic signaling via adenosine receptor modulation, potentially providing neuroprotective effects on dopaminergic neurons through A2A receptor interaction. This mechanism may explain epidemiological findings of an inverse association between caffeine intake and Parkinson’s disease risk [138]. The list of the most important positive and adverse effects of caffeine ingestion is presented in Table_1.

POSITIVE VS ADVERSE EFFECTS OF CAFFEINE INGESTION	
Blocking the perception of pain transmitted from peripheral nerves to the CNS [128]	Inducing anxiety, nausea, and vomiting at doses of 6–9 mg/kg [113]
Relieving chronic headaches, migraines, and postoperative pain [128]	Increasing urine output, tachycardia, and heart palpitations at doses exceeding 9 mg/kg [104]
Enhancing blood flow and oxygen delivery to active muscles during physical exercise [129]	Being associated with hypertension, cardiac arrhythmias, seizures, and even fatality at doses of 2000 mg/day [1,115]
Improving memory and cognitive functions [130,131]	Contributing to sleep disturbances [117]
Reducing the risk of type 2 diabetes [132]	Triggering panic attacks in individuals with anxiety or panic disorders [118–121]
Increasing perception and vigor [133,134]	Elevating the risk of cardiovascular diseases with prolonged use [126,127]
Providing potential protection against diet-induced NAFLD [135]	Enhancing bone resorption and weakening bone strength at a dose of 110.88 mg/kg [136]
Demonstrating potential in managing osteoporosis and related osteolytic conditions at a dose of 55.44 mg/kg [136]	

Potentially decreasing the risk of Parkinson's disease [137,138]	

Table_1: Positive vs Adverse Effects of Caffeine Ingestion.

CHAPTER 5: Ethics of Caffeine Usage in Sport

Due to its potential to enhance sport performance caffeine was banned in 1984 by the International Olympic Committee. Maximal concentration of caffeine in urine was set to 15 μg/ml. It was later reduced to 12 μg/ml [139]. Contemporary research paper claimed that urine level of just 10 μg/ml may suggest ingestion of caffeine with the intention of improving physical performance [140] as for example in 70-kg person, who drank 6 regular-size cups of coffee 1 hour before the exercise caffeine concentration of urine should be around proposed limit of 12 μg/ml [141]. It is the amount, which could already affect athletes performance. However, in 2004 International Olympic Committee together with WADA decided to allow usage of caffeine and WADA moved it to The Monitoring Program to detect potential patterns of misuse in sport in the future [139]. As of 2024 caffeine is still listed in WADA's Monitoring Program, among other stimulants like: bupropion, nicotine, phenylephrine, phenylpropanolamine, pipradrol and synephrine [142].

CONCLUSIONS

Caffeine is one of the most popular substances used in everyday life and sport. It can enhance physical performance and its use in sport is not banned. Caffeine is listed as a stimulant by WADA's 2024 Monitoring Program. Many factors can contribute to caffeine's effect on sport performance like regular caffeine consumption, smoking, dietary vegetable intake, pregnancy, training status, hormone replacement therapy and genetics. Typically caffeine is ingested one hour before exercise in doses around 3-6 mg/kg. In such circumstances it raises metabolic rate, increases FFA mobilization, extends time to exhaustion in both running and cycling, improves MVC and enhances high-speed muscular activity with low-load movements. It is also capable of blocking pain perception. All of these findings underline caffeine's usefulness in endurance and strength sports. Although higher doses of caffeine can help with high-load activities, the results are inconsistent and they are associated with more frequent adverse effects. Thus adequate ready-to-use protocols including training status, timing and amount of doses are yet to be researched. Moreover, such protocols should be exercise-dependent. Caffeine can also be used post-exercise, as ingestion with CHO can lead to accelerated muscle glycogen regeneration and can alleviate DOMS. Despite obvious desirable effects of caffeine it is not free of side effects, which should be taken into account before ingestion. This may be especially helpful to athletes with short time for regeneration between training sessions or during competition. Caffeine can negatively affect sleep efficiency, latency and total sleep duration time. Other side effects can include anxiety, nausea, and vomiting, increased urine output, tachycardia, heart palpitations, and anxiety. Especially high doses can present significant health risks, potentially causing severe conditions such as hypertension, cardiac arrhythmias, seizures, and even death. Before using caffeine in sport it should be considered if the positive effects of caffeine are more substantial than potential side effects. In the future it may be helpful to consider a sportsperson's genetics in determining the usefulness of caffeine in one’s workout schedule.

DISCLOSURE

AUTHOR'S CONTRIBUTION:

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