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Caffeine Sources and Exercise Performance: A Narrative Review of Anhydrous Caffeine, Coffee, and Energy Drinks

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Abstract

Background: Caffeine is a widely used ergogenic aid available as anhydrous caffeine, coffee, and energy drinks. These sources differ in dosing accuracy, composition, and practical application, which may affect exercise performance.

Aim: This review aimed to compare the effects of anhydrous caffeine, coffee, and energy drinks on exercise performance and to assess whether ergogenic responses depend mainly on caffeine dose or also on source and product composition.

Material and methods: A narrative review supported by a structured search of PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar was conducted. Original studies, systematic reviews, meta-analyses, position stands, and relevant mechanistic publications were included, with emphasis on direct comparisons using equivalent or similar caffeine doses.

Results: Anhydrous caffeine provides the greatest dosing precision and the most standardized evidence. Coffee may produce comparable effects, particularly in endurance exercise, although caffeine content is more variable. Energy drinks may improve selected outcomes, but their multi-ingredient composition limits interpretation. Responses are also influenced by dose, timing, exercise type, habitual intake, genetic variability, individual sensitivity, and sleep-related effects.

Conclusions: Current evidence does not show clear superiority of one caffeine source. Similar doses may produce comparable effects in selected protocols, but more direct comparative studies are needed. Caffeine use should be individualized and tested during training.

Keywords: caffeine supplementation; anhydrous caffeine; coffee; energy drinks; exercise performance; ergogenic aids

1. Introduction

Caffeine is one of the most widely studied and commonly used ergogenic aids in sport. Evidence indicates that it may improve endurance, muscular endurance, strength, anaerobic power, and exercise speed, with the most consistent effects observed at doses of approximately

3–6 mg/kg of body mass [1, 2, 3]. Its ergogenic action is primarily associated with antagonism of adenosine receptors, which may increase alertness, reduce perceived exertion and fatigue, and support neuromuscular function [3].

Caffeine is available in several forms, including anhydrous caffeine, coffee, energy drinks, gels, sports drinks, and chewing gums. These sources differ in caffeine concentration, dosing accuracy, additional ingredients, and practical mode of administration [3, 4, 5]. Anhydrous caffeine allows precise dosing, whereas coffee and energy drinks contain additional compounds that may modify the overall physiological response [3, 5].

Coffee contains chlorogenic acids and other bioactive substances in addition to caffeine. Available evidence suggests that caffeinated coffee may produce ergogenic effects comparable to those of isolated caffeine [5, 6]. In a direct comparison, coffee and an equivalent dose of anhydrous caffeine similarly improved cycling time-trial performance [6]. However, the caffeine content of coffee may vary depending on preparation method and serving size [5].

Energy drinks are typically multi-ingredient products containing caffeine, taurine, carbohydrates, B vitamins, and other substances. Although they may improve selected aspects of performance, it is often difficult to determine whether these effects result from caffeine alone or from interactions between ingredients [7]. Quinlivan et al. found similar improvements in cycling performance after Red Bull and an equivalent dose of anhydrous caffeine, without an additional benefit from the energy drink formulation [8].

Although the ergogenic effects of caffeine are well established, comparatively fewer studies have directly compared different caffeine sources under equivalent dosing conditions [5, 6, 8].

Research Objective

The objective of this review is to summarize and critically evaluate the effects of different caffeine sources on exercise performance, with particular emphasis on anhydrous caffeine, coffee, and energy drinks.

The review also aims to assess whether differences in ergogenic effects are primarily related to caffeine dose or whether product composition and mode of delivery also influence performance outcomes.

Research Problems

The following research problems were formulated:

1. Does the source of caffeine influence the magnitude of its ergogenic effect?

2. Is coffee as effective as an equivalent dose of anhydrous caffeine in improving exercise performance?

3. Do energy drinks provide additional performance benefits beyond those produced by isolated caffeine?

4. Do differences in product composition, dosing accuracy, and additional bioactive ingredients influence the response to caffeine?

5. How do dose, timing of ingestion, habitual caffeine intake, exercise type, and individual characteristics modify the effects of different caffeine sources?

Review Hypotheses

The following review hypotheses were proposed:

1. Caffeine improves selected aspects of exercise performance regardless of whether it is consumed as anhydrous caffeine, coffee, or an energy drink, provided that an effective dose is delivered.

2. Coffee produces ergogenic effects similar to those of an equivalent dose of anhydrous caffeine, particularly in endurance exercise.

3. Energy drinks do not consistently provide greater ergogenic benefits than isolated caffeine when comparable caffeine doses are administered.

4. The source of caffeine may influence practical aspects of its use, including dosing accuracy, tolerability, and consistency of the response, even when differences in the magnitude of the ergogenic effect are small.

5. Individual factors and differences in study protocols contribute substantially to the variability of findings concerning different caffeine sources.

2. Research Materials and Methods

This study was conducted as a narrative review supported by a structured literature search. The review focused on the effects of different caffeine sources on exercise performance, with particular emphasis on isolated or anhydrous caffeine, coffee, and energy drinks. Original experimental studies, systematic reviews, meta-analyses, consensus statements, position stands, and relevant mechanistic or pharmacokinetic publications were considered.

2.1. Participants

No participants were directly recruited for this review. The original studies included in the analysis involved healthy adults, recreationally active individuals, trained participants, and competitive athletes of both sexes.

Studies involving children, clinical populations, or participants with serious medical conditions were excluded when their findings could not be reasonably applied to healthy adults engaged in physical activity or sport.

2.2. Procedure / Search Protocol / Measures

A structured literature search was conducted in PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. The databases were searched from inception, and the final literature search was completed on 11 July 2026. Reference lists of relevant systematic reviews, meta-analyses, position stands, and eligible original studies were additionally screened to identify further publications.

The main search strategy was adapted to the requirements of each database and included combinations of the following terms:

("caffeine" OR "caffeine supplementation" OR "anhydrous caffeine" OR "isolated caffeine" OR "coffee" OR "caffeinated coffee" OR "energy drink" OR "energy drinks" OR "caffeine source" OR "caffeine delivery")

AND

("exercise performance" OR "sports performance" OR "endurance" OR "strength" OR "muscular endurance" OR "power" OR "sprint" OR "high-intensity exercise" OR "time trial").

Additional targeted searches combined caffeine-related terms with "adverse effects," "side effects," "sleep," "recovery," "habitual caffeine consumption," "tolerance," "CYP1A2," "ADORA2A," "genetic variability," "sex differences," and "training status."

For Google Scholar, the first 100 results ranked by relevance were screened. Duplicate records were removed manually.

Original performance studies were eligible when they:

1. investigated an identifiable source or form of caffeine;
2. included healthy adults, physically active individuals, or athletes;
3. evaluated at least one exercise-related performance outcome;
4. reported sufficient information regarding caffeine source, dose, timing of ingestion, comparator, or product composition;

5. were published in English.

Mechanistic, pharmacokinetic, methodological, safety-related, sleep-related, and genetic publications were additionally included when they directly supported the interpretation of the exercise-performance evidence. Eligible sources included peer-reviewed journal articles, systematic reviews, meta-analyses, consensus statements, position stands, and authoritative academic book chapters published in English.

Animal studies, conference abstracts, editorials, commentaries, case reports, and publications without relevance to caffeine use, exercise performance, or the interpretation of ergogenic responses were excluded. Multi-ingredient supplements other than the energy drinks central to the review were excluded when caffeine content was not reported or when the role of the caffeine-containing product could not be meaningfully interpreted.

The selection process was conducted in two stages. Titles and abstracts were initially screened for relevance, followed by assessment of the full texts of potentially eligible publications. Particular attention was given to randomized, placebo-controlled, crossover, and direct comparative studies evaluating different caffeine sources at equivalent or similar caffeine doses.

The main performance outcomes included endurance performance, time-trial results, time to exhaustion, muscular strength and endurance, anaerobic power, sprint performance, sport-specific activity, and perceived exertion. Additional outcomes included adverse effects, sleep-related consequences, recovery, habitual caffeine consumption, genetic variability, sex-related differences, and training status.

2.3. Data Collection and Analysis

Data were extracted on study design, participant characteristics, sample size, sex, training status, caffeine source, caffeine dose, timing of ingestion, comparator, exercise protocol, performance outcomes, adverse effects, and main findings.

The performance evidence was organized into three principal categories:

1. isolated or anhydrous caffeine;
2. coffee;
3. energy drinks.

Findings were synthesized descriptively and comparatively. Particular emphasis was placed on studies directly comparing coffee or energy drinks with an equivalent or similar dose of anhydrous caffeine.

Differences in caffeine dose, product composition, habitual caffeine consumption, participant characteristics, timing of ingestion, exercise modality, genetic variability, and study methodology were considered when interpreting inconsistent findings. Systematic reviews, meta-analyses, consensus statements, and position stands were used to place the findings of individual experimental studies within the broader evidence base.

Mechanistic and pharmacokinetic publications were used to explain caffeine absorption, metabolism, adenosine-receptor antagonism, and potential sources of interindividual variability. Safety- and sleep-related studies were used to assess the balance between acute ergogenic benefits and possible adverse consequences.

No formal risk-of-bias tool or certainty-of-evidence framework, such as GRADE, was applied. Descriptions presented in the tables therefore represent a qualitative summary of the amount, consistency, and general direction of the available evidence rather than a formal rating of evidence certainty.

2.3.1. Statistical Software

No statistical software was used because the review did not include a quantitative meta-analysis or an independent statistical analysis of participant-level data. Extracted information was organized in structured tables for descriptive comparison.

2.3.2. Statistical Methods

No original inferential statistical analyses were performed. The findings reported in the included publications were evaluated qualitatively.

Where available, mean differences, percentage changes, effect sizes, confidence intervals, and statistical significance were considered. Results were not statistically pooled because of substantial heterogeneity in caffeine sources, doses, product composition, participant characteristics, exercise protocols, and reported outcomes.

3. Results: Literature Findings

3.1. Mechanisms of Caffeine Action and Pharmacokinetics

Caffeine is rapidly absorbed after oral ingestion and is widely distributed throughout body tissues, including the central nervous system. Peak plasma concentrations are generally reached within approximately 30–120 minutes, although the exact timing may vary according to the formulation, vehicle, and conditions of ingestion [3, 9, 10]. Caffeine readily crosses the blood–brain barrier and is metabolized primarily in the liver by cytochrome P450 1A2, with paraxanthine being its principal metabolite. Only a small proportion is excreted unchanged in urine [9].

The main ergogenic mechanism of caffeine is its non-selective antagonism of adenosine receptors, particularly A_1 and A_2A receptors. By reducing the inhibitory effects of adenosine in the central nervous system, caffeine may increase alertness, improve motor activation, and reduce perceived exertion and fatigue during exercise [3, 11]. Lower perceived effort may be one of several pathways through which caffeine supports exercise performance [12].

Caffeine may also influence neuromuscular function, calcium release, substrate utilization, and motor-unit recruitment. However, some peripheral effects have been observed mainly at concentrations higher than those usually achieved after typical ergogenic doses. Therefore, central nervous system mechanisms are currently considered more important than the previously proposed effects on fat oxidation and muscle glycogen sparing [3, 13].

The pharmacokinetics and effects of caffeine vary considerably between individuals. Genetic variability in CYP1A2 activity, habitual caffeine intake, smoking, medication use, hormonal factors, and other environmental influences may alter caffeine metabolism and the duration of its effects [10, 14]. These differences may contribute to variability in both performance benefits and adverse effects following caffeine consumption [3, 10, 14].

3.2. Caffeine Sources and Exercise Performance

Caffeine is consumed in several forms that differ in dosing accuracy, composition, and practical application. Anhydrous caffeine is commonly used in controlled studies, whereas coffee and energy drinks are more representative of caffeine intake in everyday sport settings. Although all these products can provide an ergogenic dose of caffeine, their effects may also depend on additional ingredients, exercise modality, and individual response [3, 5, 7].

3.2.1. Anhydrous Caffeine

Isolated caffeine, most commonly administered as anhydrous caffeine in capsules or powder, is the most extensively investigated form in controlled exercise studies because it allows accurate dose standardization. Evidence indicates that caffeine can improve several aspects of physical performance, with the most consistent effects generally observed at doses of approximately 3–6 mg/kg of body mass [3]. Aerobic endurance appears to show the most reliable benefit, although positive effects have also been reported for muscular endurance, strength, power, sprinting, and sport-specific activities.

An umbrella review of published meta-analyses found that caffeine improved aerobic endurance, muscular strength and endurance, power, jumping performance, and exercise speed. However, the magnitude and certainty of the effects varied among performance outcomes [2]. In endurance exercise, a systematic review and meta-analysis showed small but meaningful improvements in mean power output and time-trial completion following acute caffeine ingestion, particularly at moderate doses of 3–6 mg/kg [15].

The effects of caffeine on strength and power appear to be smaller and less consistent than those observed in endurance exercise. A meta-analysis by Grgic et al. demonstrated improvements in upper-body maximal strength and muscle power, although evidence for lower-body strength was less conclusive [16]. In team sports, acute caffeine intake may produce modest improvements in selected variables, including jumping, sprinting, agility, and high-intensity activity. Nevertheless, not all sport-specific outcomes respond equally, and considerable variation exists between individuals and study protocols [17]. Studies using isolated caffeine provide the most standardized body of evidence concerning caffeine's ergogenic effects, although the magnitude of benefit depends on exercise modality and individual response.

3.2.2. Coffee

Coffee is a widely available natural source of caffeine that also contains chlorogenic acids, polyphenols, and numerous other bioactive compounds. Current evidence suggests that caffeinated coffee may improve performance across activities ranging from brief power tasks to aerobic exercise, although positive effects have not been observed in every study [5].

Recent evidence indicates that findings obtained with isolated caffeine should not be transferred directly to coffee-based strategies, because the two approaches differ in dose control, accompanying bioactive compounds, and practical application. Head-to-head interpretation is complicated by unequal experimental control. Caffeine capsules permit accurate dose matching and effective blinding, whereas coffee protocols vary in preparation method, serving volume, accompanying nutrients, caffeine content, and the success of participant blinding [18].

Hodgson et al. directly compared coffee with an equivalent dose of anhydrous caffeine during endurance exercise. Both conditions provided 5 mg/kg of caffeine and similarly improved cycling time-trial performance compared with placebo and decaffeinated coffee. No meaningful difference was observed between coffee and isolated caffeine, suggesting that coffee can provide comparable endurance benefits when the caffeine dose is sufficiently standardized [6]. Evidence concerning strength and sprint performance is more variable. Trexler et al. observed no superiority of coffee or anhydrous caffeine over placebo for the measured strength outcomes. During repeated cycling sprints, however, reductions in peak power and total work were evident in the placebo group but were less apparent following either caffeine-containing intervention [19]. Richardson et al. reported that caffeinated coffee increased total weight lifted during the squat protocol compared with placebo, whereas decaffeinated coffee supplemented with caffeine produced a greater result than decaffeinated coffee, anhydrous caffeine, and placebo. No significant differences were observed during the bench-press protocol [20].

Coffee may also improve shorter endurance-running performance. In trained male runners, caffeinated coffee consumed 60 minutes before exercise improved one-mile race time by approximately 1.3% compared with decaffeinated coffee and 1.9% compared with placebo [21]. These findings indicate that coffee can be an effective pre-exercise caffeine source. However, variability in bean type, brewing method, serving size, and caffeine content may make accurate dosing more difficult than with anhydrous caffeine [5].

3.2.3. Energy Drinks

Energy drinks are multi-ingredient products that usually combine caffeine with substances such as taurine, carbohydrates, B vitamins, and herbal extracts. Their effects on exercise performance may therefore depend on both the caffeine dose and the overall product formulation. According to the International Society of Sports Nutrition, the principal ingredients responsible for the acute ergogenic effects of most energy drinks are likely caffeine and, under some exercise conditions, carbohydrates. Evidence supporting additional benefits from many other ingredients remains limited [7].

In a direct comparison, Quinlivan et al. found that both Red Bull and an equivalent dose of anhydrous caffeine improved cycling time-trial performance. No significant difference was detected between the two caffeine-containing conditions, indicating that the additional ingredients in the energy drink did not provide a measurable advantage in that exercise protocol [8].

Positive results have also been reported in team-sport settings. Lara et al. showed that an energy drink providing 3 mg/kg of caffeine increased countermovement-jump height, peak sprint speed, total running distance, the number of sprint bouts, and the distance covered at sprinting speed during a simulated match in female soccer players [22]. However, findings are not uniformly positive. Gwacham and Wagner reported that a caffeine–taurine energy drink did not improve repeated-sprint performance or anaerobic power in collegiate American football players. The authors noted that participants' habitual caffeine use may have influenced their responses to the beverage [23].

Overall, energy drinks may improve selected aspects of endurance and team-sport performance when they provide an effective caffeine dose. Nevertheless, their multi-ingredient composition, variation between commercial formulations, and inconsistent findings make it difficult to determine whether they offer benefits beyond those of an equivalent dose of isolated caffeine. The principal characteristics of the comparative studies are summarized in Table 1.

Table 1. Summary of selected studies evaluating caffeine-containing products and exercise performance

Study	**Participants**	**Caffeine source**	**Dose**	**Exercise protocol**	**Main findings**
Hodgson et al. [6]	8 trained male cyclists and triathletes	Coffee vs anhydrous caffeine	5 mg/kg	Cycling time trial	Both coffee and anhydrous caffeine similarly improved cycling time-trial performance compared with placebo and decaffeinated coffee.
Trexler et al. [19]	54 resistance-trained men	Coffee vs anhydrous caffeine	300 mg anhydrous caffeine or coffee providing approximately 303 mg caffeine	Strength and repeated cycling sprints	No superiority over placebo for strength outcomes; repeated-sprint performance was better maintained after coffee and anhydrous caffeine.
Richardson et al. [20]	9 resistance-trained men	Coffee, caffeine and decaffeinated	0.15 g/kg caffeinated coffee; 5 mg/kg anhydrous	Squat and bench-press protocols	Caffeinated coffee increased total weight lifted during the squat protocol compared

		coffee with caffeine	caffeine; 0.15 g/kg decaffeinated coffee plus 5 mg/kg caffeine		with placebo, whereas decaffeinated coffee supplemented with caffeine produced a greater result than decaffeinated coffee, anhydrous caffeine, and placebo. No significant differences were observed during the bench-press protocol.
Clarke et al. [21]	13 trained male runners	Caffeinated coffee	3 mg/kg caffeine provided as 0.09 g/kg caffeinated coffee	One-mile running trial	Coffee improved running time compared with placebo and decaffeinated coffee
Quinlivan et al. [8]	11 trained male cyclists	Energy drink vs anhydrous caffeine	3 mg/kg caffeine provided as Red Bull or anhydrous caffeine	Cycling time trial	Both conditions improved performance; the energy drink provided no additional advantage
Lara et al. [22]	18 semiprofessional female soccer players	Caffeinated energy drink	3 mg/kg	Simulated soccer match	The energy drink improved countermovement-jump height, peak sprint speed, total running distance, the number of sprint bouts, and distance covered at sprinting speed.

Gwacham and Wagner [23]	20 male collegiate football players	Caffeine–taurine energy drink	120 mg caffeine and 200 mg taurine, corresponding to approximately 1.2 mg/kg caffeine	Repeated sprints	No significant improvement in sprint or anaerobic performance

3.3. Comparative Effects and Factors Modifying the Ergogenic Response

3.3.1. Comparative Effects of Different Caffeine Sources

Limited direct comparisons indicate that different caffeine sources may produce broadly similar effects in selected exercise protocols when comparable caffeine doses are provided. In endurance exercise, coffee containing 5 mg/kg of caffeine improved cycling time-trial performance to a similar extent as an equivalent dose of anhydrous caffeine [6]. However, serial sprint performance was better preserved after both coffee and anhydrous caffeine than after placebo [19].

Similarly, an energy drink and an equivalent dose of anhydrous caffeine produced comparable improvements in cycling time-trial performance, without a measurable additional benefit from the other ingredients present in the energy drink [8]. Together, these limited findings suggest that caffeine dose may be more influential than source in some acute exercise settings. Nevertheless, the limited number of direct head-to-head studies and the differences between exercise protocols prevent definitive conclusions. Coffee may be less precise for dosing because its caffeine content varies [5], whereas the multi-ingredient composition of energy drinks makes it difficult to isolate the independent contribution of caffeine [7].

Comparisons between coffee and isolated caffeine are also limited by methodological differences. Isolated caffeine enables precise dosing, effective placebo control, and greater intervention standardization, whereas coffee-based studies vary in brewing method, serving size, caffeine content, co-ingested nutrients, and participant blinding. Consequently, similar nominal caffeine doses do not necessarily produce identical physiological exposure or performance responses [18].

Table 2. Practical comparison of isolated/anhydrous caffeine, coffee, and energy drinks

Characteristic	Isolated/anhydrous caffeine	Coffee	Energy drinks	Supporting sources
Dosing accuracy	High; enables precise dose adjustment according to body mass	Variable because caffeine content depends on bean type, preparation method, serving size, and product	Generally more predictable than coffee when the caffeine content per serving is declared, although concentrations, serving sizes, and formulations differ between products.	[3, 5, 7]
Additional ingredients	Usually minimal or absent	Contains chlorogenic acids, polyphenols, and numerous other bioactive compounds	Commonly contains taurine, carbohydrates, B vitamins, and other ingredients	[5, 7]
Standardization in research	High; commonly used in controlled experimental studies	Moderate; dose can be standardized experimentally, but natural variability remains	Moderate to low because commercial products differ in composition	[3, 6, 7, 18]
Summary of findings for endurance performance	Generally consistent evidence of small ergogenic benefits, particularly for endurance performance	Several studies report benefits when an effective caffeine dose is provided, although direct comparisons remain limited	Positive effects have been reported in some studies, but findings vary across products and exercise protocols	[5–8, 15]

Summary of findings for strength and muscular endurance	Small benefits have been reported for selected strength, power, and muscular-endurance outcomes, but findings are not consistent across all measures	Few studies are available, and findings differ according to the exercise and outcome assessed	Findings are inconsistent and difficult to interpret because products differ in caffeine dose and additional ingredients	[7, 16, 19, 20]
Summary of findings for sprint and high-intensity performance	Some studies report improvements in sprinting, jumping, agility, and high-intensity activity, but results vary across protocols	Few studies are available, and findings are mixed	Both positive and neutral findings have been reported in sprint and team-sport protocols	[17, 19, 22, 23]
Direct comparison with isolated caffeine	Reference form for comparisons	May produce similar effects when caffeine doses are equivalent	May produce similar effects in selected protocols, without a consistent additional benefit from other ingredients	[6, 8, 19]
Main practical advantage	Precise, reproducible, and easily individualized dose	Widely available, familiar, and practical for habitual coffee consumers	Convenient ready-to-consume formulation	[3, 5, 7, 18]
Main practical limitation	Less representative of habitual dietary caffeine intake	Variable caffeine content and less precise dose standardization.	Multi-ingredient composition, variable sugar content, and difficulty isolating	[5, 7, 18]

			the effect of caffeine	
Potential adverse effects	Mainly dose-dependent, including anxiety, palpitations, gastrointestinal symptoms, and sleep disruption	Depend primarily on caffeine dose, timing of consumption, and individual sensitivity.	Depend on caffeine dose, product composition, serving size, and possible combined intake with other stimulants	[3, 5, 7, 24, 25]
Overall interpretation	Provides the greatest dosing precision and is commonly used as a reference form in controlled exercise studies.	May be an effective alternative to isolated caffeine when the dose is sufficient and reasonably standardized	May improve selected outcomes, but evidence does not consistently demonstrate superiority over an equivalent dose of isolated caffeine	[3, 5–8, 18]

Note: The statements presented in the table summarize the amount, consistency, and general direction of findings in the cited literature. They do not represent a formal assessment of evidence certainty using GRADE or another standardized evidence-rating framework.

3.3.2. Dose and Timing of Caffeine Intake

Caffeine dose is an important determinant of both performance benefits and adverse effects. The most consistent ergogenic responses are generally observed following doses of approximately 3–6 mg/kg of body mass. Higher doses do not necessarily produce greater performance improvements and may increase the likelihood of adverse effects [3]. Low doses may also be effective in some individuals, indicating that the minimum effective dose can vary. Caffeine is commonly consumed approximately 60 minutes before exercise, particularly when administered in capsules. However, optimal timing may depend on the delivery form, exercise duration, individual metabolism, and whether caffeine is consumed before or during exercise [3]. Standard recommendations may therefore not be equally appropriate for all athletes, and individualized strategies may be required to identify an effective dose and timing protocol [26].

Recent meta-analytic evidence indicates that acute caffeine intake increases the likelihood of several self-reported side effects in athletes. Tachycardia, insomnia, abdominal discomfort, and anxiety were among the most consistently reported effects, while dose–response analyses indicated that the risk of several symptoms increased with caffeine dose. Low-to-moderate doses of up to 6 mg/kg may therefore provide a more favorable tolerability profile than doses above 6 mg/kg [24]. From a practical perspective, a dose near 3 mg/kg may provide performance benefits while limiting the frequency and severity of unwanted symptoms [25].

3.3.3. Habitual Caffeine Consumption

Regular caffeine intake has traditionally been considered a potential cause of tolerance and a reduced ergogenic response. However, current evidence does not consistently support this assumption. A systematic review and meta-analysis found that habitual caffeine consumption did not significantly alter the acute effects of caffeine on exercise performance [27].
Similarly, caffeinated coffee providing 3 mg/kg of caffeine improved 5-km cycling time-trial performance in participants with both low and high habitual caffeine consumption, with no meaningful difference in the magnitude of improvement between the groups [28]. Habitual intake may nevertheless remain relevant when interpreting withdrawal symptoms and individual perceptions of caffeine, and should therefore be considered when developing a supplementation strategy [3, 26].

3.3.4. Genetic Variability, Sex, and Training Status

Interindividual variability in the response to caffeine may be partly related to genetic factors. The genes most frequently investigated are CYP1A2, which is involved in caffeine metabolism, and ADORA2A, which encodes an adenosine receptor associated with the physiological and psychological response to caffeine [29].
A systematic review and meta-analysis found that caffeine generally improved performance among individuals with the CYP1A2 AA and AC genotypes, whereas results for CC carriers were less favorable. However, the small number of participants with the CC genotype, baseline differences between genotype groups, and variation in dose and timing limit the certainty of these findings [30]. These findings suggest a possible genetic contribution to caffeine responsiveness, but the current evidence does not yet justify basing routine supplementation recommendations solely on CYP1A2 genotype.

Sex-related differences have also been investigated as potential modifiers of caffeine responsiveness. However, studies directly comparing women and men have generally not demonstrated consistent differences in aerobic performance or fatigue responses following caffeine intake [31].

Training status has also been investigated as a potential moderator of caffeine responsiveness. However, available evidence does not establish it as a consistent predictor of ergogenic effects, and direct comparative studies remain limited [32].

3.3.5. Sleep, Recovery, and Practical Individualization

The acute performance benefits of caffeine should be considered together with its potential effects on sleep and recovery. Studies in athletes have reported variable effects of caffeine on sleep duration, quality, efficiency, awakenings, and sleep-onset latency, with outcomes differing according to the supplementation and exercise protocols [33].

Insomnia was also identified as one of the most consistently reported adverse effects of acute caffeine intake in athletes. This finding reinforces the need to consider not only immediate performance benefits but also the potential consequences of caffeine ingestion for subsequent sleep and recovery [24].

The risk of sleep disruption is particularly relevant when caffeine is consumed before training or competition held later in the day. Any acute performance benefit should therefore be weighed against the possibility that disrupted sleep could compromise subsequent recovery [33]. Sleep-related adverse effects appear to be more common with higher doses, although sensitive individuals may also experience them after moderate caffeine intake [25, 33].

Overall, caffeine supplementation should be individualized according to the athlete's effective dose, preferred source, habitual intake, sensitivity to adverse effects, exercise type, competition schedule, and sleep requirements. Current evidence suggests that source alone is unlikely to explain all differences in the ergogenic response. Instead, performance outcomes appear to result from interactions among caffeine dose, timing, individual characteristics, exercise demands, and product composition.

4. Discussion and Future Directions

The available evidence confirms that caffeine can improve selected aspects of exercise performance, particularly endurance, although benefits have also been reported for muscular endurance, strength, power, sprinting, and sport-specific activity [2, 3]. However, the magnitude of the ergogenic effect varies considerably according to exercise modality, caffeine dose, timing of ingestion, participant characteristics, and study design.

Direct comparisons suggest that the amount of caffeine consumed may be more important than its source in some exercise settings. Coffee and anhydrous caffeine produced similar improvements in endurance cycling when equivalent caffeine doses were provided, while an energy drink did not outperform an equivalent dose of isolated caffeine [6, 8]. Nevertheless, these findings are based on a limited number of direct comparative studies and should not be generalized to all products, exercise protocols, or athlete populations. Evidence concerning strength, sprint, and other high-intensity exercise outcomes is generally more variable than the evidence for endurance performance [2, 3], as also illustrated by the mixed findings reported by Trexler et al. [19].

Each caffeine source also presents distinct practical advantages and limitations. Anhydrous caffeine enables accurate dosing and is therefore useful in controlled research and individualized supplementation [3]. Coffee is widely available and may provide comparable ergogenic effects, but its caffeine content varies according to serving size, bean type, and preparation method [5]. Energy drinks may be convenient, but their multi-ingredient composition makes it difficult to determine whether observed effects result from caffeine, carbohydrates, or other substances [7].

The choice of caffeine source may depend on the practical objective. A standardized supplement is advantageous when reproducible dosing is essential, whereas coffee may better reflect usual dietary behavior. Early recovery studies suggest a possible benefit of coffee combined with carbohydrates for post-exercise glycogen restoration, but the evidence remains sparse and lacks matched head-to-head comparisons [18].

Individual variability remains an important limitation in the interpretation of caffeine research. Habitual caffeine intake does not appear to consistently eliminate the acute ergogenic response, although it should still be considered when interpreting individual responses and possible withdrawal effects [3, 27]. Although genetic variability may contribute to differences in caffeine responsiveness, the available evidence does not yet justify basing routine supplementation recommendations solely on genotype [29, 30]. Evidence concerning sex-related differences remains limited, partly because women have been underrepresented in many caffeine studies [31]. The role of training status is also not fully established, and direct comparisons between trained and recreationally active participants remain limited [32].

Another important consideration is the balance between immediate performance benefits and adverse effects. A recent systematic review included 48 studies involving 940 athletes, of which

38 were eligible for meta-analysis. Acute caffeine intake increased the likelihood of several side effects, and the risk of some symptoms rose with increasing caffeine dose. These findings strengthen the rationale for using the lowest effective dose and individualizing caffeine intake according to tolerance, exercise demands, and competition timing [24]. This is particularly relevant when caffeine is consumed later in the day, because any immediate performance benefit should be weighed against the possibility of poorer subsequent sleep and recovery [33]. Therefore, caffeine strategies should be tested during training and individualized according to dose tolerance, timing, exercise demands, habitual intake, and sleep schedule.

Future studies should directly compare anhydrous caffeine, coffee, and energy drinks using equivalent caffeine doses, standardized timing, and identical exercise protocols. Larger randomized crossover trials are needed, particularly among women, elite athletes, and individuals representing different habitual caffeine intakes and genetic profiles. Research should also report individual responses rather than relying exclusively on group means.

Further investigation is required to determine whether bioactive compounds in coffee or additional ingredients in energy drinks modify the effects of caffeine. Studies should clearly report product composition, actual caffeine content, dietary intake, sleep, adverse effects, and participant blinding. Longer-term research is also needed to assess repeated caffeine use, tolerance, recovery, sleep, and the consequences of supplementation across consecutive training or competition days.

Overall, current evidence suggests that caffeine dose and individual characteristics may be at least as important as caffeine source in determining the ergogenic response. However, the limited number of well-controlled head-to-head studies prevents definitive conclusions regarding the comparative superiority of anhydrous caffeine, coffee, or energy drinks.

5. Conclusions

Caffeine is an effective ergogenic aid that can improve selected aspects of exercise performance, particularly endurance, although benefits have also been reported for strength, muscular endurance, power, sprinting, and sport-specific activity. Limited direct evidence suggests that anhydrous caffeine, coffee, and energy drinks may produce broadly similar effects in selected exercise protocols when comparable caffeine doses are provided.

Anhydrous caffeine offers the greatest dosing precision, whereas coffee may provide a practical and effective alternative despite variability in caffeine content. Energy drinks may also enhance

performance, but their multi-ingredient composition makes it difficult to determine whether they provide benefits beyond those attributable to caffeine alone.
The ergogenic response is influenced not only by caffeine source, but also by dose, timing of ingestion, exercise modality, habitual caffeine intake, individual sensitivity, genetic variability, and possible effects on sleep. Therefore, caffeine use should be individualized and tested during training before being applied in competition.
Current evidence does not support the clear superiority of one caffeine source over another. More direct comparative studies using equivalent caffeine doses and standardized exercise protocols are needed to determine whether product composition and mode of delivery independently influence performance outcomes.

DISCLOSURE

Author's Contributions

Conceptualization: Izabela Czerny, Szymon Daniszewski;
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