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Short Title: Low versus high caffeine doses

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Abstract

Caffeine is a popular and widely utilised sporting ergogenic aid. Over the years, the effects of different caffeine doses have been researched, with the general consensus being that 3-6 mg/kg of caffeine represents the optimal caffeine dose for most people. Recently there has been increased attention placed on lower (≤3 mg/kg) caffeine doses, with some research suggesting these doses are also ergogenic. However, a critical consideration for athletes is not merely whether caffeine is ergogenic at a given dose, but whether the consumed dose provides an optimised performance benefit. Following this logic, we identify a potential oversight in the current research relating to the efficacy of lower caffeine doses. Although low caffeine doses do appear to bestow ergogenic effects, these effects have not been adequately compared to the currently accepted best practice dose of 3-6 mg/kg. This methodological oversight limits the practical conclusions we can extract from the research into the efficacy of lower doses of caffeine, as the relative ergogenic benefits between low and recommended doses remains unclear. Here, we examine existing research with a critical eye, and provide recommendations both for those looking to utilise caffeine to enhance their performance, and those conducting research into caffeine and sport.

Key Words: Caffeine, ergogenic, low-dose, supplement, sports drink

1. Introduction

Of all sporting ergogenic aids, caffeine (1,3,7-trimethylxanthine) is the most popular, with approximately 75% of athletes consuming it either before or during competition [1,2]. Indeed, caffeine has such a reliable performance enhancing effect that, for over twenty years (1984-2004), high doses were banned for within-competition use by the World Anti-Doping Agency (WADA), and caffeine remains on their active monitoring programme to this day. The ergogenic effects of caffeine ingestion have been demonstrated across a wide range of sports, including endurance [3] and team sports [4], and across different exercise methods and modalities, including repeated high-intensity efforts [5], muscular endurance [6], maximum strength [7] and anaerobic performance [8].

Whilst the ergogenic effects of caffeine have been known for over 100 years [9], the broad array of potential mechanisms by which caffeine exerts its performance enhancing effects have only more recently been more fully elucidated. The most well-established mechanism is that of caffeine's role as a competitive adenosine receptor antagonist [10], dampening adenosine's downregulation of Central Nervous System arousal [11]. In turn, this promotes the release of a spectrum of neuro-chemicals, including dopamine and the excitatory neurotransmitter glutamate [12], thereby increasing muscle firing rates [13]. Caffeine also stimulates adrenaline secretion [14], alters substrate utilization and metabolism [15], and increases cellular ion release [16]. More recently, the relationship between caffeine, pain, and exercise performance has been explored, with current evidence suggesting that caffeine decreases pain perception, which in turn reduces rating of perceived exertion (RPE) [17] and enhances exercise capacity [18]. Latterly, it has been proposed that caffeine's bitter taste may drive some of its performance enhancing benefits [19], in a similar fashion to the documented effects of the bitter tasting compound quinine [20]; such observations may explain the ergogenic effects of caffeine-infused mouth-rinses [21].

Given that caffeine's effects have been extensively researched, and consistently, reliably and repeatedly demonstrated to improve—and only very rarely shown to harm [22]—exercise performance, it's use is pervasive amongst both professional and amateur athletes alike [1,2]. This extensive use has resulted in the formulation of best practice guidelines by numerous professional bodies. The International Society of Sports Nutrition’s position stand on caffeine [23], for example, summarizes that caffeine is effective at enhancing performance at dosages considered to be moderate (~3-6 mg/kg), consumed approximately 60 minutes prior to performance, with no additional ergogenic effects seen with higher caffeine doses (>9 mg/kg). Such recommendations have been echoed elsewhere, both in the scientific literature [14,16] and lay press. Interestingly, however, a number of studies have recently shown that lower doses of caffeine, typically of ≤3 mg/kg, are also ergogenic [24]. In this article, we examine the evidence underpinning this finding, and explore whether low doses (≤3 mg/kg) of caffeine pre-exercise offer comparable ergogenic benefits to the more conventionally recommended intakes (3-6 mg/kg); such an examination is crucial, as athletes are likely interested in whether their caffeine dose offers the *maximal* ergogenic benefits, as opposed to just *an* ergogenic effect. Finally, we note some methodological recommendations that researchers may wish to consider when conducting low dose caffeine research in the future.

2. Are low doses of caffeine ergogenic?

Whilst, historically, high doses (up to 13 mg/kg) of caffeine have been used to induce ergogenic effects [25], more recently there has been an increasing focus on the use of more moderate (~3-6 mg/kg) caffeine doses [26]. The success of these trials in turn has prompted research investigating the efficacy of lower doses of caffeine (≤3 mg/kg). Whilst the number of these trials is relatively low, a recent review by Spriet [24] concluded that these lower caffeine doses, when consumed prior to exercise, likely enhanced athletic performance. Similarly, a recent meta-analysis of the ergogenic effects of caffeine-containing energy drinks, the majority of which had a dose of ≤3 mg/kg, concluded that ingestion of these drinks improved performance [27]. Accordingly, in general, the evidence to date supports the perspective that lower doses of caffeine are ergogenic for sports performance, particularly with regards to endurance sport. However, perhaps a more pertinent consideration for athletes is whether these low doses of caffeine are as effective in enhancing performance as the more conventional, higher doses? As athletes consume caffeine primarily to improve performance, and presumably wish to improve their performance to the maximum amount possible, this is an important consideration. If low doses of caffeine are ergogenic, but not as ergogenic as higher doses, then athletes consuming these lower doses may be leaving some potential performance improvements on the table. As such, the question as to whether or not low (≤3 mg/kg) doses of caffeine exert similar ergogenic effects as more conventional, moderate (3-6 mg/kg) doses seems highly relevant.

There are two ways by which we could determine whether low doses of caffeine are as ergogenic as higher doses. Firstly, we could compare the magnitude of improvements seen between studies; for example, determining whether the size of the ergogenic effect is greater in those studies that utilise 6 mg/kg compared to 2 mg/kg. This superficially simple approach, however, is surprisingly problematic, because the magnitude of caffeine-derived performance enhancement is highly variable between both trials and subjects [28]. As illustration, consider the array of variables which interact to modulate caffeine ergogenesis; genotype [22,29,30], training status [31], habitual caffeine use [32], sex [33], caffeine source [34], age [35], expectancy [36], exercise type [37], and time of day of exercise [38]. Given the extensive differences between study methodologies and recruited populations, it seems unlikely that such a comparison would provide the desired, and necessary, conceptual clarity.

Instead, a better option might be to have low-dose and high-dose caffeine trials within each study, thereby allowing for a direct comparison between the different caffeine doses. Although seemingly sensible, such an approach is surprisingly uncommon. In a recent review, Spriet [24] concluded that low caffeine doses (≤3 mg/kg), taken before exercise, enhanced athletic performance compared to placebo. However, the vast majority of the studies included in Spriet's [24] review (summarized in table 1) did not directly compare a low dose (≤3 mg/kg) of caffeine with a higher dose (>3 mg/kg). In fact, only 4 of the 14 studies did so [39-42]. Of these four, there were mixed results; two reported no additional benefits from 6 mg/kg of caffeine compared to 3mg/kg of caffeine when examining aerobic endurance performance [39,41]; one reported that 4.5 mg/kg enhanced aerobic endurance performance to a greater extent than 3.2 mg/kg, which in turn was more ergogenic than a dose of 2.1 mg/kg [40]; and one found that 5 mg/kg enhanced maximum knee flexion and extension isokinetic torque, whilst 2 mg/kg did not [42]. The remaining studies either did not use a caffeine dose above 3 mg/kg in their comparison [43-45], or only used a single caffeine dose (≤3 mg/kg), and compared this to placebo [46-52]. We identified additional papers published following Spriet's [24] review that directly examined a low versus high dose of caffeine [22,53-56]. Of these, Arazi and colleagues [53] reported no difference in performance between a low (2 mg/kg) and high (5 mg/kg) caffeine dose—a finding replicated by Guest and colleagues [22] with doses of 2 and 4 mg/kg on a 10kg cycle ergometer time trial—whilst others [53-

55] reported mixed results, in part because of the large number of performance tests utilised. Interestingly, Sabol and colleagues [56] reported similar improvements in vertical jump performance following ingestion of 2, 4, and 6 mg/kg of caffeine, whilst upper body ballistic exercise performance was only enhanced following a dose of 6 mg/kg. Consequently, due to both the equivocal results of the small numbers of trials directly investigating this phenomenon, and the lack of higher caffeine doses utilised in other trials, it is unclear whether lower doses of caffeine are as ergogenic as higher doses. Recently, Talanian & Spriet [57] suggested that, based on their interpretations of five lower-dose caffeine studies [26,40,43,44,57] that the timing of the lower caffeine dose may be a crucial aspect, with ingestion less than 60 minutes pre-exercise associated with a greater performance benefit than later ingestion (80-180 minutes pre-exercise).

Study	**Subjects**	**Caffeine Timing**	**Exercise**	**Caffeine Dose**	**Comparison to best practice?**	**Finding**
Graham and Spriet [39]	8 well-trained males	60 minutes pre-exercise	TTE run at 85% VO2max	0 (placebo), 3, 6, & 9 mg/kg	Yes	Endurance was equally enhanced in both 3 and 6 mg/kg caffeine trials
Kovacs et al. [40]	15 well-trained males	60% of solution 60 minutes pre-exercise, and 20% at two time points within	1-hour maximum cycle	0 (Placebo), 2.1, 3.2, 4.5 mg/kg	Yes	Performance was enhanced to the greatest extent in 4.5 mg/kg, then 3.2 mg/kg, then 2.1 mg/kg.

		exercise trial.				
Jenkins et al. [44]	13 trained male cyclists	60 minutes pre-exercise	15 minutes VO2 peak performance cycle	0 (placebo), 1, 2, 3 mg/kg	No	Compared to placebo, only 2 mg/kg significantly enhanced performance
Desbrow et al. [43]	9 trained male cyclists	60 minutes pre-exercise	120 min steady state cycle, followed by TT.	0 (placebo), 1.5, 3 mg/kg	No	No performance enhancement with caffeine
Irwin et al. [50]	12 trained male cyclists	90 minutes pre-exercise	Cycle TT	0 (placebo) or 3 mg/kg	No	Caffeine enhances performance compared to placebo
Desbrow et al. [41]	16 trained cyclists	90 minutes pre-exercise	60 min cycle at 75% peak sustainable power	0 (placebo), 3, 6 mg/kg	Yes	No additional benefit of 6 mg/kg compared to 3 mg/kg
Wiles et al. [46]	34 male athletes	60 minutes pre-exercise	1500m run	~150-200 mg from coffee (3g total coffee)	No	Caffeine enhanced performance.
Van Nieuwenhoven et al. [47]	98 well trained male and females	At start, 4.5, 9 and 13.5 km of exercise trial	18km run	90 mg	No	No effect of caffeine

Bridge & Jones [48]	8 male runners	60 minutes pre-exercise	8km race	0 (Placebo), 3 mg/kg, or no suppleme nt.	No	Caffeine enhanced performance.
Schubert et al. [45]	6 male runners	65 minutes pre-exercise	5km run TT	0 (placebo), 80 mg, 140 mg)	No	No differences in caffeine consumption trials when compared to placebo.
Perez-Lopez et al. [52]	13 elite female volleyball players	60 minutes pre-exercise	Volleyball specific tests	0 (placebo) and 3 mg/kg	No	Caffeine enhanced performance.
Del Coso et al. [51]	15 male volleyball players	60 minutes pre-exercise	Volleyball specific tests	0 (placebo) and 3 mg/kg	No	Caffeine enhanced performance.
Strecker et al. [49]	10 male tennis players	90 minutes pre-exercise	Tennis skill performance	0 (placebo) and 3 mg/kg	No	Caffeine enhanced performance.
Astorino et al. [42]	15 active males	60 minutes pre-exercise	40 maximal knee extensions	0 (placebo), 2, 5 mg/kg	Yes	Only the 5mg/kg dose enhanced performance.
Talanian & Spriet [57]	15 cyclists (n=4 female)	40 (~42% total), 20 (~33%	Time to completion cycle	0 (placebo),	No	Higher caffeine dose enhanced time-trial

		total) and 0 (~25%) minutes pre-time trial	ergometer test	~1.5, ~2.9 mg/kg		performance to a greater extent than lower dose.
Tallis & Yavuz [55]	10 active males	60 minutes pre-exercise	Isokinetic concentric and eccentric strength at 60 & 180 deg/s of elbow and knee flexors	0 (placebo), 3 and 6 mg/kg	Yes	No effect of caffeine on elbow flexor (concentric and eccentric) or knee (eccentric) flexor strength. Both caffeine doses increased concentric force in knee extensors at 180 deg/s, with no difference between doses. Only the higher (6 mg/kg) dose enhanced force during repeated contractions.
Turley et al. [54]	26 young (8-10y) boys	60 minutes pre-exercise	Hand grip and Wingate tests..	0, (placebo), 1, 3 and 5 mg/kg	Yes	Grip strength – significantly higher in 3 and 5 mg/kg caffeine trials. Wingate – 3 mg/kg produced greatest peak power, whilst

						5 mg/kg produced greatest mean power.
Arazi et al. [53]	10 female karate athletes	60 minutes pre-exercise	1RM leg press, leg press repetitions to failure, vertical jump, RAST test.	0 (placebo), 2 and 5 mg/kg	Yes	No significant difference in test performance between groups.
Sabol et al [56]	20 recreationally active males	60 minutes pre-exercise	Medicine ball throw and vertical jump	0 (placebo), 2, 4, and 6 mg/kg	Yes	No difference between caffeine doses in terms of lower body performance enhancement. Only 6 mg/kg enhanced upper body performance.
Guest et al [22]	101 competitive males	~45 minutes pre-exercise	10km cycle ergometer time trial	0 (placebo), 2 and 4 mg/kg	Yes	No difference in performance enhancement between caffeine doses; both enhanced performance compared to placebo.

TTE – Time-to-exhaustion; VO_{2max} - maximal oxygen consumption; TT – Time Trial

Table 1 – A summary of studies examining the impact of low doses of pre-exercise caffeine on sports performance. For the purposes of this table, a low dose of caffeine is defined as 3mg/kg or less. (Adapted from Spriet [24]; studies that did not utilise a pre-exercise caffeine dose, or those that only used a caffeine dose greater than 3mg/kg, were excluded, and additional relevant papers published since that review have been added). 1RM; one repetition maximum. RAST; running-based anaerobic sprint test.

3. A potential solution?

This is not to suggest that these methodological shortcomings are the fault of researchers. Commonly, investigations are designed to explore phenomena tangentially bordering, but not directly targeting, this experimental question. However, based on our interpretation of the research, it is clear that, to decisively answer this question, additional trials that directly compare low caffeine doses with those falling into line with the currently accepted optimal dose (3-6 mg/kg), are required. Such research would remove much of the existing ambiguity permeating caffeine research. An equivalent approach is considered best-practice in the realm of medical drug development, where randomised controlled trials are designed to directly compare new drugs with the best currently available treatment as the optimal approach [58]. Accordingly, it is not sufficient to demonstrate that a new intervention is more effective than placebo, but that it produces better results than the currently accepted best treatment.

An illustrative example is that of research into caffeinated chewing gum, an increasing popular ergogenic aid in sport [19]. Studies investigating the ergogenic effects of caffeinated gum on aerobic endurance performance are currently equivocal. As per a recent review [19]. two studies [59,60] reported no ergogenic effect of caffeinated gum on aerobic endurance performance, whilst three studies [61-63] reported a positive effect. An obvious distinction between these trials is the dose; the “no effect” findings occurred following a dose of 200 mg, whilst the positive effect trials employed a dose of 300 mg. If we assume an average subject mass of ~80 kg, then 200 mg of caffeine would be classed as a low dose, and 300 mg would fall within the recommended optimal threshold. Here, the inclusion of a trial utilising a currently accepted optimal caffeine dose in the 200 mg studies would potentially resolve the current ambiguity.

Additionally, there is contemporary debate regarding the impact of regular caffeine consumption on the subsequent ergogenic effects of caffeine, with some studies finding a negative impact of habituation [32], whilst others report none [64]. One potential outcome is that regular caffeine use requires a subsequently larger caffeine dose to exert performance benefits [65]. As such, the dose of caffeine used in experimental trials substantially influences study conclusions, particularly when exploring the effects of habitual use. Recently, Evans and colleagues [66] explored the influence of caffeinated gum, supplying 200 mg of caffeine, on repeated sprint performance in team sport athletes. The initial finding was that caffeine did not confer any ergogenic effects; however, further analysis demonstrated that habitual caffeine use modified the performance enhancement seen following caffeine ingestion; in this case, very low habitual caffeine users (<40 mg/d) did exhibit ergogenic effects, whilst more moderate habitual users (>130 mg/d) did not. Such findings may be interpreted as evidence that habitual use reduced caffeine's ergogenic effects. However, an obvious question emerges; what if the dose of caffeine used was within the currently accepted guidelines, as opposed to <3 mg/kg? As this wasn't explored, the answer remains unclear. Again, this is not an attack on the authors, who were exploring a different research question, but it nevertheless underscores the point that increasingly robust conclusions could be inferred from caffeine research if the currently accepted optimal dose was included.

4. How robust is the currently accepted optimal dose?

For the purposes of this review, we have defined the currently accepted optimal dose of caffeine as between 3 and 6 mg/kg. This figure is based on a number of different reviews and positions stands [14,23]. Furthermore, it is not suggested that there are any additional ergogenic effects associated with a dose above this [25]. However, there is considerable inter-individual variation in the ergogenic effects of caffeine ingestion [68]. This phenomenon becomes apparent when caffeine studies report individual subject data. Jenkins et al. [44], for example, examined the effects of lower caffeine doses (1, 2, and 3 mg/kg) compared to placebo on a 15-minute maximum cycle. Of the 13 subjects, one did not exhibit an ergogenic effect at any dose, whilst four found caffeine ergogenic at every dose, but to different extents. Graham and Spriet [39] demonstrated that 9 mg/kg of caffeine improved time-to-exhaustion in seven subjects, but with the percentage improvements compared against the placebo trial varying from 105-250%. Neither of these studies utilised the currently accepted optimal caffeine dose, so whether the findings would have been replicated under those conditions remains unclear. Nevertheless, the results serve to illustrate the extent of inter-individual responses to caffeine. Furthermore, some studies report no ergogenic effect of caffeine [67], again illustrating that the individual response to a standardised dose of caffeine is highly variable. The drivers of the variation of wide and varied, but can be grossly summarised as genetic, environmental (i.e. non-genetic), and epigenetic factors [68].

4.1 Genetic

Variation within *CYP1A2*, the gene encoding for cytochrome P450 1A2—the enzyme responsible for 95% of all caffeine metabolism [69]—has been shown to affect caffeine metabolization speed. Here, individuals with a C allele metabolise caffeine slower than AA genotypes [70]. Potentially, this single nucleotide polymorphism (SNP) might impact caffeine ergogenicity, with C allele carriers exhibiting lower [29] or no [22] ergogenic effects. However, these findings are currently tentative, with other studies reporting the opposite [71], or no effect [72] of this polymorphism on performance. The mechanism underpinning this reduced ergogenic effect in C allele carriers is currently unclear. Guest and colleagues [22] suggest that, because caffeine is a vasoconstrictor, slow metabolisers experience this vasoconstriction for a longer period of time, inhibiting the delivery of oxygen and nutrients to the working muscle. Conversely, Womack and colleagues [29] suggest that the downstream metabolites of caffeine (paraxanthine, theobromine, and theophylline) confer their own ergogenic effect; in this case, the presence of these metabolites would be lower in C allele carriers than AA genotypes at a given time point due to the slower metabolization of caffeine. As such, it's not clear whether caffeine has a reduced ergogenic, or even an ergolytic, effect in C allele carriers, or whether they need to ingest caffeine a greater amount of time before exercise [73]. Similarly, there is the potential that a SNP in *ADORA2A*, which encodes for a sub-type of adenosine receptor, may underpin some of the individual variation in response to caffeine, in terms of ergogenicity [30], anxiety [74], and sleep disturbances [75].

4.2 Environmental

Alongside these genetic drivers are environmental determinants of individual variation in the response to caffeine, which include age [35], training status [31], habitual caffeine use [32,65], diet [76], medication use [77], and personal belief as to whether caffeine enhances performance [36].

4.3 Epigenetics

Habitual caffeine use likely induces long-term epigenetic changes [78,79], which may in turn affect future ergogenic effects, potentially by increasing caffeine metabolization speed [80]. For example, habitual caffeine use increases CYP1A2 activity [81], thereby increasing caffeine clearance, which may alter the expected ergogenic effects of caffeine ingestion. Additionally, long-term exposure to caffeine may alter its stimulatory effects, partly mediated by inhibition of genes affecting the adenosine pathway [82].

Accordingly, whilst caffeine is ergogenic, the currently accepted optimal caffeine dose may not be optimal for everyone [68]. Some individuals may benefit from lower doses of caffeine (discussed below), whilst others may need higher doses. Nevertheless, at present the abundance of evidence does suggest that, for most people, most of the time, a caffeine dose of between 3-6 mg/kg likely is sufficient to realise the optimum ergogenic effects. Indeed, Burke [83] suggested that the dose-response relationship of caffeine on performance appears to plateau at around 3 mg/kg. As such, this dose may represent a target threshold to maximise caffeine's ergogenic effects, although higher doses are indeed ergogenic, and in some cases may be required, such as in habitual users [65]. Sensibly, the recommendations of 3-6 mg/kg should be taken as a starting point, from which individual experimentation can be used to refine pre-training and pre-competition caffeine strategies.

5. When might lower doses of caffeine be more appropriate?

The purpose of this article is not to discount the ergogenic potential of lower doses of caffeine; indeed, available evidence suggests that these lower doses can enhance performance [24]. Furthermore, the use of lower doses of caffeine may be preferential in certain situations. Higher doses of caffeine, for example, appear to be more likely to induce negative side-effects, such as anxiety [84] and sleep disturbances [85]. From a sporting perspective, both of these outcomes have the potential to negatively impact performance [86,87]. Furthermore, sleep disturbances following caffeine ingestion may reduce recovery from exercise and/or competition, and subsequently harm physical performance the following day [87]. In these cases, individual athletes need to make informed, strategic decisions negotiating the trade-off between the optimised ergogenic effects seen with higher doses of caffeine against the potential for increased anxiety or compromised sleep. Here, the context is critical; arguably, the athlete would be more concerned with sleep disturbances if there is a high priority competitive bout in the proceeding few days, such as during the heats at the Olympic Games, as opposed to an Olympic Final, when no subsequent performance is required. Conversely, athletes predisposed to greater pre-competition anxiety may wish to consume less caffeine prior to important competitions than they would for lower level competitions and training, as caffeine may exacerbate this anxiety-promoting predisposition.

Similarly, differences in genotype may predispose individuals to respond well to lower doses of caffeine. Preliminary evidence suggests, for example, that moderate doses of caffeine (4 mg/kg) are harmful to endurance performance in *CYP1A2* genotypes [22]. However, a dose of 2 mg/kg showed no performance decrement, suggesting that lower doses for these individuals may be more favourable than higher doses. Whilst further clarification is required, the potential for genetically-guided caffeine recommendations to be made, with certain genotypes potentially responding better to lower caffeine doses, remains a future possibility [68,73].

Regular ingestion of lower doses of caffeine may also guard against habituation to higher doses, which has been shown to negatively affect the ergogenic benefits of a caffeine dose [32,65], although this remains equivocal [64]. There is the potential that regular ingestion of caffeine increases the amount of caffeine required to realise the ergogenic effects, such that if an athlete habitually consumed 3 mg/kg of caffeine pre-training, they might require a caffeine dose closer to 6 mg/kg pre-competition [65]. This may increase the potential for adverse side effects, and, if the habitual dose increases over time, might take the athlete to a point in which further increases in dose don't restore the optimised ergogenic effect of caffeine. In this scenario, habitual use of lower caffeine doses (~3 mg/kg) may facilitate an increased pre-competition dose, thereby allowing for both enhancement of regular training, along with competition performance.

6. Conclusions

In summary, the existing research is clear that low doses of caffeine are ergogenic [24]. However, to derive more robust conclusions there is an evident need within these studies for a direct comparison with the currently accepted optimal caffeine dose (>3 to 6 mg/kg). The majority of studies that support the ergogenic benefits of low doses of caffeine do not compare these low doses to the caffeine doses more typically considered to be ergogenic. As a result, whilst low doses of caffeine do offer a performance benefit, it's not clear that this performance benefit is greater than, or indeed equal to, that offered by caffeine doses between 3 and 6 mg/kg. The addition of a caffeine trial utilising 3-6 mg/kg of caffeine would therefore greatly aid in the interpretation of such findings, and so should be considered in future research.

We hope that the points raised here enable athletes, coaches, support staff, and perhaps even researchers to better critique the studies underpinning their caffeine strategies and recommendations. Moving forward, we also recommend that caffeine researchers include a trial that utilizes the currently accepted optimal dose of caffeine – even if this dose is not optimal for everyone – in order to enable more direct comparisons between studies, and thereby enabling firmer conclusions to be made. Finally, as per our previous explorations of caffeine use in sport [65,68], we urge athletes and practitioners to experiment with different caffeine doses, timing, and ingestion methods in order to uncover the strategies best suiting their unique genetic predispositions, environmental influences, and individual histories.

Novelty Statement & Practical Applications

This critical review has demonstrated that, whilst lower doses (≤3 mg/kg) of caffeine have the potential to be ergogenic, it's not clear whether such doses are as ergogenic as higher doses. The main cause of this uncertainty is due to a lack of trials directly comparing low and high doses of caffeine. As such, athletes, coaches and practitioners looking to utilise caffeine as a means to enhance performance would be best placed to experiment with various different caffeine doses in order to determine the optimal dose to enhance their performance, given their own unique biology, history, and performance requirements.

Compliance with Ethical Standards

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516