Title: Are low doses of caffeine as ergogenic as higher doses? A critical review highlighting the need for comparison to current best practice in caffeine research.

Short Title: Low versus high caffeine doses

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Are low doses of caffeine as ergogenic as higher doses? A critical review highlighting the need for comparison to current best practice in caffeine research.

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
3 mg/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-
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).

<table>
<thead>
<tr>
<th>Study</th>
<th>Subjects</th>
<th>Caffeine Timing</th>
<th>Exercise</th>
<th>Caffeine Dose</th>
<th>Comparison to best practice?</th>
<th>Finding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graham &amp; Spriet [39]</td>
<td>8 well-trained males</td>
<td>60 minutes pre-exercise</td>
<td>TTE run at 85% VO2max</td>
<td>0 (placebo), 3, 6, &amp; 9 mg/kg</td>
<td>Yes</td>
<td>Endurance was equally enhanced in both 3 and 6 mg/kg caffeine trials</td>
</tr>
<tr>
<td>Kovacs et al. [40]</td>
<td>15 well-trained males</td>
<td>60% of solution 60 minutes pre-exercise, and 20% at two time points within</td>
<td>1-hour maximum cycle</td>
<td>0 (Placebo), 2.1, 3.2, 4.5 mg/kg</td>
<td>Yes</td>
<td>Performance was enhanced to the greatest extent in 4.5 mg/kg, then 3.2 mg/kg, then 2.1 mg/kg.</td>
</tr>
<tr>
<td>Study</td>
<td>Participants</td>
<td>Pre-exercise</td>
<td>Exercise</td>
<td>NO</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Jenkins et al. [44]</td>
<td>13 trained male cyclists</td>
<td>60 minutes pre-exercise</td>
<td>15 minutes VO2 peak performance cycle</td>
<td>0 (placebo), 1, 2, 3 mg/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desbrow et al. [43]</td>
<td>9 trained male cyclists</td>
<td>60 minutes pre-exercise</td>
<td>120 min steady state cycle, followed by TT.</td>
<td>0 (placebo), 1.5, 3 mg/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irwin et al. [50]</td>
<td>12 trained male cyclists</td>
<td>90 minutes pre-exercise</td>
<td>Cycle TT</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Desbrow et al. [41]</td>
<td>16 trained cyclists</td>
<td>90 minutes pre-exercise</td>
<td>60 min cycle at 75% peak sustainable power</td>
<td>0 (placebo), 3, 6 mg/kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wiles et al. [46]</td>
<td>34 male athletes</td>
<td>60 minutes pre-exercise</td>
<td>1500m run</td>
<td>No</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Van Nieuwenhoven et al. [47]</td>
<td>98 well trained male and females</td>
<td>At start, 4.5, 9 and 13.5 km of exercise trial</td>
<td>18km run</td>
<td>No</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Jenkins et al. [44]**: Compared to placebo, only 2 mg/kg significantly enhanced performance.
- **Desbrow et al. [43]**: No performance enhancement with caffeine.
- **Irwin et al. [50]**: Caffeine enhances performance compared to placebo.
- **Desbrow et al. [41]**: No additional benefit of 6 mg/kg compared to 3 mg/kg.
- **Wiles et al. [46]**: Caffeine enhanced performance.
- **Van Nieuwenhoven et al. [47]**: No effect of caffeine.
<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Intervention</th>
<th>Outcome measure</th>
<th>Dose (placebo)</th>
<th>Supplement</th>
<th>Performance Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridge &amp; Jones [48]</td>
<td>8 male runners</td>
<td>60 minutes pre-exercise</td>
<td>8km race</td>
<td>0 (Placebo), 3 mg/kg, or no supplement.</td>
<td>No</td>
<td>Caffeine enhanced performance.</td>
</tr>
<tr>
<td>Schubert et al. [45]</td>
<td>6 male runners</td>
<td>65 minutes pre-exercise</td>
<td>5km run TT</td>
<td>0 (placebo), 80 mg, 140 mg</td>
<td>No</td>
<td>No differences in caffeine consumption trials when compared to placebo.</td>
</tr>
<tr>
<td>Perez-Lopez et al. [52]</td>
<td>13 elite female volleyball players</td>
<td>60 minutes pre-exercise</td>
<td>Volleyball specific tests</td>
<td>0 (placebo) and 3 mg/kg</td>
<td>No</td>
<td>Caffeine enhanced performance.</td>
</tr>
<tr>
<td>Del Coso et al. [51]</td>
<td>15 male volleyball players</td>
<td>60 minutes pre-exercise</td>
<td>Volleyball specific tests</td>
<td>0 (placebo) and 3 mg/kg</td>
<td>No</td>
<td>Caffeine enhanced performance.</td>
</tr>
<tr>
<td>Strecker et al. [49]</td>
<td>10 male tennis players</td>
<td>90 minutes pre-exercise</td>
<td>Tennis skill performance</td>
<td>0 (placebo) and 3 mg/kg</td>
<td>No</td>
<td>Caffeine enhanced performance.</td>
</tr>
<tr>
<td>Astorino et al. [42]</td>
<td>15 active males</td>
<td>60 minutes pre-exercise</td>
<td>40 maximal knee extensions</td>
<td>0 (placebo), 2, 5 mg/kg</td>
<td>Yes</td>
<td>Only the 5mg/kg dose enhanced performance.</td>
</tr>
<tr>
<td>Talanian &amp; Spriet [57]</td>
<td>15 cyclists (n=4 female)</td>
<td>40 (~42% total), 20 (~33%)</td>
<td>Time to completion cycle</td>
<td>0 (placebo),</td>
<td>No</td>
<td>Higher caffeine dose enhanced time-trial</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Study</th>
<th>Participants</th>
<th>Time before exercise</th>
<th>Test</th>
<th>Dose</th>
<th>Effect</th>
<th>Performance to lower dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tallis &amp; Yavuz [55]</td>
<td>10 active males</td>
<td>60 minutes</td>
<td>Isokinetic concentric and eccentric strength at 60 &amp; 180 deg/s of elbow and knee flexors</td>
<td>0 (placebo), 3 and 6 mg/kg</td>
<td>Yes</td>
<td>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.</td>
</tr>
<tr>
<td>Turley et al. [54]</td>
<td>26 young (8-10y) boys</td>
<td>60 minutes</td>
<td>Hand grip and Wingate tests..</td>
<td>0, (placebo), 1, 3 and 5 mg/kg</td>
<td>Yes</td>
<td>Grip strength – significantly higher in 3 and 5 mg/kg caffeine trials. Wingate – 3 mg/kg produced greatest peak power, whilst</td>
</tr>
<tr>
<td>Study</td>
<td>Participants</td>
<td>Time Pre-exercise</td>
<td>Test</td>
<td>Doses</td>
<td>Caffeine Effect</td>
<td>Notes</td>
</tr>
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<tr>
<td>Arazi et al. [53]</td>
<td>10 female karate athletes</td>
<td>60 minutes</td>
<td>1RM leg press, leg press</td>
<td>0 (placebo), 2 and 5 mg/kg</td>
<td>Yes</td>
<td>5 mg/kg produced greatest mean power.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pre-exercise</td>
<td>repetitions to failure, vertical jump, RAST test.</td>
<td></td>
<td></td>
<td>No significant difference in test performance between groups.</td>
</tr>
<tr>
<td>Sabol et al [56]</td>
<td>20 recreationally active males</td>
<td>60 minutes</td>
<td>Medicine ball throw and vertical jump</td>
<td>0 (placebo), 2, 4, and 6 mg/kg</td>
<td>Yes</td>
<td>No difference between caffeine doses in terms of lower body performance enhancement. Only 6 mg/kg enhanced upper body performance.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pre-exercise</td>
<td>Med. Ball throw and Vertical jump</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Guest et al [22]</td>
<td>101 competitive males</td>
<td>~45 minutes</td>
<td>10km cycle ergometer time trial</td>
<td>0 (placebo), 2 and 4 mg/kg</td>
<td>Yes</td>
<td>No difference in performance enhancement between caffeine doses; both enhanced performance compared to placebo.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pre-exercise</td>
<td>10km cycle ergometer time trial</td>
<td></td>
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</tbody>
</table>
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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**References:**


