Is coffee a useful source of caffeine pre-exercise?

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Abstract

Caffeine is a well-established ergogenic aid, with its performance-enhancing effects demonstrated across a wide variety of exercise modalities. Athletes tend to frequently consume caffeine as a performance enhancement method in training and competition. There are a number of methods available as a means of consuming caffeine around exercise, including caffeine anhydrous, sports drinks, caffeine-carbohydrate gels, and gum. One popular method of caffeine ingestion in non-athletes is coffee, with some evidence suggesting it is also utilized by athletes. In this article, we discuss the research pertaining to the use of coffee as an ergogenic aid, exploring (a) whether caffeinated coffee is ergogenic, (b) whether dose-matched caffeinated coffee provides a performance benefit similar in magnitude to caffeine anhydrous, and (c) whether decaffeinated coffee consumption affects the ergogenic effects of a subsequent isolated caffeine dose. There is limited evidence that caffeinated coffee has the potential to offer ergogenic effects similar in magnitude to caffeine anhydrous; however, this requires further investigation. Co-ingestion of caffeine with decaffeinated coffee does not seem to limit the ergogenic effects of caffeine. Whilst caffeinated coffee is potentially ergogenic, its use as a pre-exercise caffeine ingestion method represents some practical hurdles to athletes, including the consumption of large volumes of liquid, and difficulties in quantifying the exact caffeine dose, as differences in coffee type and brewing method may alter caffeine content. The use of caffeinated coffee around exercise has the potential to enhance performance, but athletes and coaches should be mindful of the practical limitations.

1. Introduction

Caffeine is a well-established ergogenic aid, with performance-enhancing effects confirmed at meta-analysis level (Grgic et al., 2019) across a variety of exercise types, including aerobic and muscular endurance, muscle strength, anaerobic power, speed, and jumping performance (Polito et al., 2016; Grgic et al., 2018; Southward et al., 2018; Grgic et al., 2019; Grgic & Pickering, 2019). Caffeine enhances performance via a variety of mechanisms, including a reduction in perceived exertion and pain perception, as well as increases in motor unit recruitment (Doherty & Smith, 2004; Graham 2001). Athletes, never slow to adopt practices that might enhance performance, are well aware of caffeine's ergogenic benefits, with approximately 75% of athletes consuming caffeine around competitions (Aguilar-Navarro et al., 2019).

Caffeine is also widely utilized by the general public, seeking to harness caffeine's positive effects on alertness (Zwyghuizen-Doorenbos et al., 1990) and concentration (Haskell et al., 2008), particularly when sleep deprived (Wesensten et al., 2005), as well as a method to harness caffeine's purported health benefits, such as a decreased risk of Parkinson's disease and type-2 diabetes (Grosso et al., 2017). The most common method of consuming caffeine is via coffee (Frary et al., 2005), with an estimated 2.25 billion cups consumed globally per day (Denoeud et al., 2014).

Like the general public, athletes regularly consume caffeine in their daily lives (Tunnicliffe et al., 2008). Alongside its direct, well-established ergogenic effects, consumption of caffeine can also offset the fatigue associated with regular, frequent training sessions (Doherty & Smith, 2005), mask training-induced soreness (Hurley et al., 2013;

Maridakis et al., 2007), or overcome sleep disruption caused by early morning training sessions and jet lag (Cook et al., 2011; Arendt, 2009). Athletes have a variety of options available when it comes to selecting how to obtain their caffeine dose. Whilst the majority of caffeine research studies utilize caffeine anhydrous, typically in tablet or capsule form (Wickham & Spriet, 2018), caffeine can also be ingested through caffeinated sports drinks (Souza et al., 2017)—with or without additional carbohydrate—alongside caffeinated bars (Hogervorst, 2008), gels (Cooper et al., 2014; Venier et al., 2019), and gum (Ryan et al., 2012), in addition to more experimental methods such as caffeinated sprays (De Pauw et al., 2017) and mouth rinses (Beaven et al., 2013). Caffeinated coffee represents an additional caffeine consumption method for athletes, with research suggesting coffee is widely used by athletes (Desbrow & Leveritt, 2006; Tunnicliffe et al., 2008), although it is not necessarily clear whether they consume coffee as a deliberate pre-exercise ergogenic aid, or via social habits.

Whilst coffee contains caffeine, it is also comprised of a variety of other components, such as chlorogenic acids (de Paulis et al., 2002), ferulic acid and caffeic acid (Hall et al., 2015). These additional components may modify the ergogenic effects of caffeine contained in coffee, either offering additional performance benefits, or reducing caffeine's performance-enhancing effects. Given the well-established ergogenic effects of caffeine (Grgic et al., 2019), and that coffee represents one of the most widely used methods of caffeine ingestion in athletes and non-athletes (Tunnicliffe et al., 2008; Denoeud et al., 2014), it is important to fully understand whether caffeinated coffee offers ergogenic benefits, and whether these benefits are similar to an equivalent dose of isolated caffeine. A previous review (Higgins et al., 2016) found that five of nine studies exploring the effects of caffeinated coffee on endurance performance reported that coffee was ergogenic, suggesting it may be a safe alternative to anhydrous caffeine as a performance-enhancer. This previous review (Higgins et al., 2016) focused only on endurance performance; however, since its publication, several other studies have been published, exploring the use of caffeinated coffee on both endurance (Clarke et al., 2018; Marques et al., 2018) and high-intensity (Trexler et al., 2016; Richardson & Clarke, 2016) performance. Furthermore, the authors of this previous review included anhydrous caffeine powder dissolved into decaffeinated coffee within their definition of caffeinated coffee. While this practice is valid in research settings, it likely does not mirror how caffeine is utilized by active populations in the real world (i.e. these individuals would likely consume either caffeinated coffee or a caffeinated supplement, being unlikely to add supplemental caffeine to decaffeinated coffee). As such, the aim of this review is to re-examine and critically review the evidence for the use of caffeinated coffee—defined as coffee in its caffeinated form, and not as decaffeinated coffee with additional caffeine anhydrous—as an ergogenic aid, with specific reference to the practical implications and limitations of utilizing coffee as a pre-exercise caffeine source, allowing athletes and practitioners to better weigh the evidence regarding the use of coffee within sporting contexts.

2. Does caffeinated coffee provide an ergogenic benefit?

Before discussing the results of individual studies, some methodological aspects warrant a brief discussion. Decaffeinated coffee generally contains very low amounts of caffeine (up to 16 mg) that might not be ergogenic, therefore allowing a valid “placebo” comparison (McClusker et al., 2006). The process of decaffeinated coffee production involves treatment of the coffee beans, which results in the reduction of the caffeine content. This process alters the content of other nutritional properties in the coffee, such as polyphenols (Silvarolla et al., 2004). This also needs to be considered from a study design perspective, ideally, the only difference between caffeinated and decaffeinated coffee should be the caffeine content. Studies exploring the ergogenic effects of coffee should employ three conditions; caffeinated coffee, decaffeinated coffee, and a beverage that mimics the taste of coffee but provides no caffeine or other nutritional properties. Of the discussed studies, only a few (Clarke and colleagues 2016 and 2018; Hodgson et al., 2013) employed such a design. Additionally, habitual caffeine use may blunt the expected ergogenic benefits of caffeine use (Lara et al., 2019), although this is currently a contentious subject (Pickering & Kiely, 2019), with a number of studies reporting no influence of habituation on caffeine's subsequent ergogenic effect (e.g. Goncalves et al., 2017; Sabol et al., 2019). Researchers often control for this by reporting the habitual caffeine use of their subjects (as detailed in the tables within this manuscript), and by requiring a period of caffeine abstinence prior to experimental trials.

A number of studies, summarized in table 1, have demonstrated that caffeinated coffee can provide an ergogenic effect above decaffeinated coffee. Wiles and colleagues (1992) demonstrated that 3g of instant caffeinated coffee, providing 150-200 mg of caffeine, significantly enhanced 1500m run performance compared to decaffeinated coffee. Clarke and colleagues (2018) compared the ergogenic effects of caffeinated coffee (providing approximately 3 mg/kg caffeine) with decaffeinated coffee and placebo on a competitive one-mile run, finding that race time was significantly faster in the caffeinated compared to decaffeinated (+1.3%; -0.06s, 95% confidence interval [CI]: -.011 to -0.01 min:s.ms) and placebo (+1.9%; -0.09, 95% CI: -0.15 to -0.03 min:s.ms) trials. No difference was observed between decaffeinated coffee and placebo, even though there was a small favouring of the decaffeinated coffee condition (+0.6%; -0.03: 95% CI: -0.09 to 0.03 min:s.ms). Hodgson and colleagues (2013) reported that caffeinated coffee (5 mg/kg of caffeine) enhanced performance in a 45-minute time trial compared to decaffeinated coffee. Demura et al, (2007) reported that caffeinated coffee ingestion (6 mg/kg caffeine; 800 to 1000 ml of fluid) decreased RPE during a 60-minute submaximal cycle ergometer task performed at 60% of maximum oxygen uptake (VO_{2max}) compared to decaffeinated coffee. However, by focusing of changes in RPE, this study did not directly measure exercise performance, which somewhat limits the practical value of these findings.

Not all studies support a performance-enhancing effect of caffeinated coffee. Graham et al. (1998) reported no difference between caffeinated coffee (caffeine dose of 4.45 mg/kg) and decaffeinated coffee in an endurance running task. Marques et al. (2018) found that caffeinated coffee (providing 5.5 mg/kg of caffeine) did not enhance 800m time trial run performance when compared to decaffeinated coffee. Lamina and Musa (2009) utilized caffeine doses of 5, 10 and 15 mg/kg, delivered through powdered coffee dissolved in 200 ml of water, finding no ergogenic effect of any caffeine dose on 20m shuttle run performance. This latter result is especially surprising, given the high caffeine doses utilized, and performance tests that typically show enhancement with acute caffeine consumption (Goldstein et al., 2010). However, from a practical standpoint the use of very high caffeine doses, such as 10 and 15 mg/kg, should be avoided given the reported side-effects of caffeine ingestion, such as gastrointestinal distress, nervousness, jitters, and others, which appear to increase with caffeine dose (Kaplan et al., 1997). Furthermore, such high acute intakes of caffeine are above the European Food Safety Authority's general safe acute intake level of 200 mg (EFSA, 2015), and so are potentially unsafe.

Regarding resistance exercise, Richardson and Clarke (2016) reported no difference between caffeinated coffee and decaffeinated coffee on a muscular endurance squat and bench press task, whilst Clarke et al. (2016) reported no benefit of caffeinated coffee compared to a placebo coffee alternative that contained no caffeine on repeated sprint performance.

INSERT TABLE 1 AROUND HERE

In summary, when compared to decaffeinated coffee, there is some evidence that caffeinated coffee, providing a typically ergogenic caffeine dose of 3-6 mg/kg, may enhance aerobic endurance performance (Wiles et al., 1992; Hodgson et al., 2013; Clarke et al., 2016), and can lower RPE during exercise (Demura et al., 2007). However, these findings are equivocal, with some authors reporting no ergogenic effect of caffeinated compared to decaffeinated coffee (Marques et al., 2018; Graham et al., 1998; Lamina & Musa 2009; Church et al., 2015; Anderson et al., 2018). The limited research regarding resistance and high-intensity exercise tentatively suggests no benefits to caffeinated coffee above decaffeinated coffee (Richardson & Clarke, 2016; Clarke et al., 2016), but this area merits further research.

3. Is this ergogenic benefit similar to that of caffeine anhydrous?

It appears that caffeinated coffee has the potential to exert ergogenic effects, at least for endurance performance, even though the somewhat limited studies to date often provide conflicting results. An important next step is to understand whether caffeinated coffee provides an ergogenic effect similar in magnitude to that of caffeine anhydrous, requiring direct comparison of caffeinated coffee and caffeine; this has been explored experimentally in a number of trials, summarized in table 2. Graham and colleagues (1998) undertook a trial in which nine trained subjects underwent five time-to-exhaustion treadmill trials at 85% of VO_{2max}, comparing differences between placebo, caffeine capsules, caffeinated coffee, decaffeinated coffee, and decaffeinated coffee with caffeine capsules, consumed ~60 minutes prior to the exercise trial. The caffeine dose was standardised across trials to deliver 4.45 mg/kg of caffeine, with a total volume of liquid of 7.15 ml/kg. Despite similar changes in plasma methylxanthines—downstream metabolites of caffeine—in all caffeinated trials, only the caffeine capsule trial significantly improved performance. These results lead to the conclusion that coffee is probably inferior to isolated caffeine as an ergogenic aid (Graham, 2001). This study included only nine participants, and has five repeated measures; as such, it is very possible that it was statistically underpowered. Additionally, it needs to be highlighted that Graham et al. (1998) used a time to exhaustion test, and these tests generally exhibit poor test-retest reliability (test-retest coefficient of variation of > 10%) (Currell & Jeukendrup, 2006). These tests appear unsuitable when exploring the acute effects of supplements given that the overall magnitude of acute improvements with most supplements—including caffeine—is likely to be small to moderate. For example, the improvements in performance following caffeine ingestion are generally in the range of 2% to 6% (Grgic et al., 2019); utilizing tests with poor reliability may, therefore, lead to type II errors. Hodgson and colleagues (2013) used a cycling time trial test, and these tests generally have a test-retest variation of < 5%. The results of this study indicated that caffeine (5 mg/kg) and caffeinated coffee (providing 5 mg/kg of caffeine) enhanced cycle time trial performance compared to decaffeinated coffee and placebo to a similar extent, suggesting that coffee was as effective as caffeine anhydrous in enhancing aerobic endurance performance.

INSERT TABLE 2 AROUND HERE

Other studies report no ergogenic effect of either caffeinated coffee or caffeine anhydrous (3 mg/kg) on performance (Clarke et al., 2016), although these studies often utilize high-intensity or resistance exercise, modalities in which the ergogenic effects of caffeine are less pronounced (Grgic et al., 2019). For example, Trexler and colleagues (2016) reported no beneficial effect of caffeinated coffee or caffeine, standardised to provide an absolute dose of ~300 mg caffeine (3.8 mg/kg), on a number of resistance training measures when compared to placebo, although both caffeinated coffee and caffeine maintained repeated cycle ergometer sprint performance when compared to placebo. This study had a between-group design, and, thus, the inter-individual variation in responses to caffeine supplementation were not as well controlled as if the researchers had utilized a cross-over design (Maclure, 1991). Clarke and colleagues (2016) reported no ergogenic effect of 3 mg/kg caffeine, or coffee providing 3 mg/kg caffeine, on power output or RPE across 18 x 4-second cycle ergometer sprints. Richardson and Clarke (2016) reported that caffeinated coffee enhanced muscular endurance performance compared to placebo, whilst caffeine alone did not, although caffeine in combination with decaffeinated coffee did.

The results in this area are, therefore, inconsistent. Whilst Graham and colleagues (1998) reported caffeine offered enhanced ergogenic benefits compared to coffee in an aerobic endurance task, conflicting findings were reported by Hodgson et al. (2013). This is potentially due to the type of performance test utilized (as noted previously), or variation in the composition and preparation of the coffee solutions (Hodgson et al., 2013). Graham et al. (1998) did not report the coffee brand utilized, limiting detailed between-study comparisons; future studies should explicitly note the exact brands of coffee within their methodologies. In terms of resistance and high-intensity exercise, it appears that, in general, caffeine and coffee perform similarly, although the identified studies report mixed findings regarding the ergogenicity of caffeine on this exercise type (Trexler et al., 2016; Richardson & Clarke, 2016; Clarke et al., 2016). Further research into the coffee versus caffeine conundrum is therefore required, especially in light of findings suggesting differences in salivary caffeine concentrations following ingestion of coffee or caffeine anhydrous (Liguori et al., 1997); might these differences in absorption rates modify the performance-enhancing effects of each caffeine modality?

4. Does decaffeinated coffee block caffeine's ergogenic effects?

There remains the possibility that other coffee constituents can modify caffeine's ergogenic effects. For example, 3,4-dicinnamoyl-1,5-quinides in coffee may raise adenosine levels (de Paulis et al., 2002). This increase in adenosine levels could subsequently counteract the ergogenic effects of caffeine on exercise performance. Specifically, after ingestion, caffeine binds to adenosine receptors, reduces perceived exertion, and ultimately enhances exercise performance (Graham, 2001). This effect of caffeine on adenosine receptors is one of the primary mechanisms underpinning its ergogenic effects (Graham 2001). Indeed, in the study by Graham and colleagues (1998), caffeinated coffee, as well as caffeine capsules consumed alongside decaffeinated coffee, did not enhance endurance performance versus placebo, whilst caffeine capsules consumed in isolation did—despite the fact that plasma methylxanthine concentrations increased similarly in the coffee- and capsule-only trials.

Historically, researchers added caffeine anhydrous to decaffeinated coffee in caffeine ingestion trials, allowing them to utilize decaffeinated coffee as a placebo. As a result, there are a number of research studies, detailed in table 3, allowing us to explore this question.

Butts and Crowell (1985) reported that caffeine, when consumed with decaffeinated coffee, did not significantly improve endurance performance when compared to a decaffeinated coffee only trial. However, the percentage improvement of 14% (+8.6 min) for females (with an average caffeine dose of ~5 mg/kg) and 3% (+2.2 min) for males (with an average caffeine dose of ~4 mg/kg) following caffeine ingestion are indicative of an effect, although this did not reach statistical significance. Similar results have been reported by Rodrigues et al. (1990). In this study, ingestion of 5 mg/kg caffeine did not affect total cycling time to exhaustion; however, this study also included a small sample size of six participants.

However, contrasting findings were reported by McLellan and Bell (2004). Here, the authors explored the impact of previous consumption of coffee, both caffeinated and decaffeinated, on the effects of subsequent caffeine supplementation on exercise performance across a range of caffeine doses, ranging from 3 mg/kg to 7 mg/kg total caffeine intake. Coffee was consumed approximately 30 minutes prior to the caffeine capsules, which in turn were consumed approximately one hour prior to an exhaustive cycle ergometer trial. Time-to-exhaustion was significantly increased following caffeine capsule ingestion, regardless of whether caffeinated or decaffeinated coffee was consumed beforehand. Trice and Haymes (1995) explored the effects of 5 mg/kg caffeine, dissolved in decaffeinated coffee, compared to decaffeinated coffee alone on intermittent cycling performance, finding that time to exhaustion was significantly increased in the caffeine compared to decaffeinated coffee trial. Similar results were reported by Costill et al. (1978), utilizing 330 mg (4.5 mg/kg) of caffeine dissolved in decaffeinated coffee. Here, caffeine ingestion enhanced total cycling time to exhaustion by approximately 15 minutes compared to decaffeinated coffee. Additionally, Richardson and Clarke (2016) found that 5 mg/kg of caffeine, consumed in combination with decaffeinated coffee, enhanced resistance exercise performance to a greater extent than caffeine anhydrous (5 mg/kg) consumed in isolation. In this study, the mean difference between the two conditions in the total number of repetitions was 3 (95% CI: 0.1 to 5.2). Such an increase in muscular endurance following acute caffeine ingestion is similar to improvements noted following eight weeks of regimented resistance training (Mattocks et al., 2017), highlighting the possible magnitude of caffeine's effects.

INSERT TABLE 3 AROUND HERE

At present, despite the results of Graham and colleagues (Graham et al., 1998) the majority of results in this area suggest that co-ingestion of caffeine with decaffeinated coffee does not limit the ergogenic effects of caffeine (Butts & Crowell, 1985; McLellan & Bell, 2004; Trice & Haymes, 1995; Costil et al., 1978), and may serve to enhance resistance training performance to a greater extent than isolated caffeine (Trexler et al., 2016), although this latter finding requires further research, especially in a cross-over type design.

5. Practical Considerations

As compared to caffeine anhydrous, coffee ingestion could provide similar ergogenic effects (Hodgson et al., 2013). In order to exert these ergogenic effects, the caffeine content likely needs to be within the commonly considered ergogenic range of 3-6 mg/kg (Goldstein et al., 2010). This is illustrated by Hodgson and colleagues (Hodgson et al., 2013), in which coffee was ergogenic at a caffeine dose of 5 mg/kg; here, this represented 600 ml of coffee, a substantial amount of liquid to have to consume prior to exercise. This is also the case in other studies; Graham and colleagues (1998) delivered 4.45 mg/kg caffeine through coffee, requiring ~600 ml of fluid, and Demura et al. (2007) required 4-5 200ml cups of coffee to deliver the required caffeine dose. These examples illustrate a practical issue surrounding coffee's use as an ergogenic aid, specifically that it potentially requires a large volume of liquid to be consumed, with an "average" cup of coffee containing approximately 100mg of caffeine (Desbrow et al., 2007). Caffeine is most reliability shown to be ergogenic at doses of between 3 – 6 mg/kg (Goldstein et al., 2010), meaning that, for a 70kg athlete, a minimum of two cups of coffee are required to reliably elicit a performance-enhancing effect at this lower threshold. Whilst caffeine can be ergogenic at lower doses (Spriet, 2014), there is considerable variation between individuals when it comes to the optimal caffeine dose (Pickering & Kiely, 2018), and aspects such as habitual caffeine use can further increase the caffeine dose required (Pickering & Kiely, 2019), although this latter topic is still controversial (Goncalves et al., 2017). Accordingly, for habitual caffeine users, caffeine doses of 6 mg/kg might be required to elicit a performance benefit, which represents over four cups of coffee for a 70kg athlete, potentially comprising over a liter of fluid. Consumption of such high amounts of fluid has the potential to lead to increased sensations of fullness during exercise, increases in body weight—an important consideration for weight class and weight-bearing sports—and may contribute to an increased risk of hyponatremia, particularly in endurance athletes (Coyle, 2004). High fluid consumption (900 ml – similar to the volume utilized by Demura and colleagues) may also divert blood flow from the muscles activated during exercise to the gastrointestinal system, which may subsequently hinder running exercise performance (Backes & Fitzgerald, 2016). It is interesting to note that large fluid intakes appear to hinder running but not cycling performance (Backes & Fitzgerald, 2016; Backx et al., 2003); this difference in exercise modes could be another explanation for the divergent results reported by Graham et al. (1998), who utilised a running test and reported no ergogenic effects of coffee, and Hodgson et al. (2013), who employed a cycling test and found coffee to be ergogenic.

A further complication regarding optimising the caffeine dose from coffee is the large variability in caffeine concentrations not just between coffee brands, but within the same brand over time (Desbrow et al., 2007; Desbrow et al., 2012; Desbrow et al., 2019). Desbrow and colleagues (2007) reported the average caffeine concentrations of 97 espresso samples collected across the Gold Coast, Australia. Whilst the mean caffeine dose per coffee was 106 mg per serving, it ranged from 25 to 214 mg (Desbrow et al., 2007). In a follow up study, it was reported that coffees purchased at the same venue at different time points had highly variable caffeine concentrations, in one case varying from 81 mg to 189 mg of caffeine in the same product (Desbrow et al., 2012). At-home coffee making fairs no better, with a recent study (Desbrow et al., 2019) reporting caffeine concentrations of Nespresso coffee pods varying from 19 to 147 mg. Whilst this issue does not solely plague coffee (Desbrow et al., 2018), it increases the difficulty of accurate quantification of the caffeine dose ingested, which may have important implications in the development of caffeine habituation (Pickering & Kiely 2019), or the experience of negative side-effects, such as increased anxiety and reduced sleep quality (Pickering & Kiely, 2018).

Additionally, coffee is often consumed hot, which may affect thermoregulatory control during exercise, modifying exercise capacity and performance (Wimer et al., 1997; Mundel et al., 2006). As such, for athletes exercising in warm and/or humid temperatures, coffee may limit exercise performance, although, to our knowledge, this has yet to be explored experimentally, and any increase in core temperature may dissipate prior to the onset of exercise. Furthermore, both caffeine and coffee have the potential to act as gastric irritants (Boekema et al., 1999). The potential for gastric discomfort is potentially higher with coffee ingestion, given the multi-ingredient nature of coffee. Accordingly, especially in coffee-naïve individuals, coffee may increase feelings of discomfort during exercise. As with any nutritional intervention, the use of coffee as an ergogenic aid should be trialed in training or competitions of lesser importance, and, similar to the "training of the gut" concept with carbohydrate ingestion (Jeukendrup, 2017), these issues could potentially be alleviated.

6. Areas for further research

Caffeine, and likely coffee, potentially exerts some of its ergogenic effects via expectancy and placebo (Shabir et al., 2018), such that when individuals believe they have consumed caffeine, and believe caffeine is ergogenic, their performance is often greater than if they believe they have not consumed caffeine (Saunders et al., 2017). As caffeine, ingested via capsules or coffee, may exert negative, performance-limiting side effects such as increased anxiety (Childs et al., 2008), the use of placebos to exert performance benefits in these cases may be advantageous, if not ethically challenging. Further research exploring the expectancy effects of caffeine, potentially using decaffeinated coffee or a coffee-like scent (Madzharov et al., 2018), may assist in bringing clarity to this area, particularly in situations where caffeine ingestion may be difficult, such as in the later stages of a prolonged endurance race.

Given the observations that lower doses of caffeine (i.e. <3 mg/kg) may be ergogenic for exercise performance (Lieberman et al., 1987; Spriet, 2014), more work is required to explore the minimal effective doses of both caffeine and caffeinated coffee. For example, if a caffeine dose of 2 mg/kg administered in the form of caffeinated coffee is ergogenic—and the research suggests it potentially is (Spriet, 2014)—it would require the ingestion of a much more reasonable volume of coffee (e.g. 1-2 espressos for a 70kg individual).

Future studies should also seek to explore the effects of cold brew or iced coffee compared to hot coffee on performance. This area might be relevant given the observations that cold water (4°C) ingestion, compared to water at room temperature (22°C), may result in different effects on bench press to muscle fatigue performance (Lafata et al., 2012). This could be especially important during exercise in hot temperatures, where ingestion of hot coffee may confer a performance limitation.

Additionally, a recent review (Loureiro et al., 2018) examined whether coffee components, primarily caffeine, caffeic acid, cafestol, and chlorogenic acid, may exert beneficial effects on muscle glycogen recovery post-exercise. Whilst the studies underpinning this review were primarily conducted in vitro or in rats, this is an area worthy of potential exploration, particularly if coffee outperforms caffeine anhydrous in this regard. However, a recent study (Nieman et al., 2018), in which participants were randomly assigned to receive either a high chlorogenic acid coffee or placebo for two weeks reported no beneficial effect of the coffee on post-exercise inflammation or oxidative stress, although there were moderate improvements in mood.

Finally, compared to research on caffeine anhydrous, there is a relative dearth of studies exploring the efficacy of coffee as the method of caffeine ingestion within exercise contexts. If active individuals are utilizing coffee as a method of ingesting caffeine—and the research suggests they are (Desbrow & Leveritt, 2006; Tunnicliffe et al., 2008)—it is important that we better understand the ergogenic effects, and potential interactions, of coffee on performance.

7. Conclusion

In summary, based on a small number of studies, it appears that:

1. Caffeinated coffee has the potential to offer ergogenic effects above placebo or decaffeinated coffee, at least in terms of aerobic exercise (Wiles et al., 1992; Hodgson et al., 2013; Graham et al., 1998).
2. There is limited evidence that caffeinated coffee offers a similar magnitude of ergogenic effect when compared to caffeine anhydrous (Hodgson et al., 2013), provided the caffeine doses are matched. However, the studies here are both conflicting and of low sample size, and therefore caution should be exercised with the interpretation of findings.
3. Prior or co-ingestion of decaffeinated coffee along with caffeine anhydrous does not appear to blunt caffeine's ergogenic effects (McLellan & Bell, 2004; Trice & Haynes, 1995), although, from a practical standpoint, it is difficult to identify a situation in which this ingestion type would occur.

At present it appears that caffeinated coffee ingestion, approximately 60 minutes prior to exercise and delivering a typically ergogenic caffeine dose (i.e. 3-6 mg/kg), represents a potential method of enhancing aerobic endurance performance (Higgins et al., 2016; Hodgson et al., 2013), with some tentative positive findings for resistance and high-intensity exercise activities (Trexler et al., 2016; Richardson et al., 2016). However, the low number of overall studies, along with both low subject numbers and opposing findings, limit the strength of this conclusion. Additionally, coffee represents a number of practical hurdles regarding its use pre-exercise, including the ingestion of potentially high volumes of (often hot) liquid, or highly concentrated brews which may irritate the gastrointestinal tract. Accurately quantifying the caffeine dose from coffee is also difficult (Desbrow et al., 2007; Desbrow et al., 2012; Desbrow et al., 2019), increasing the potential for negative side effects or a lack of ergogenic effect due to under-dosing with caffeine. Finally, there is the possibility that other constituents in coffee modify both performance and recovery, although this is poorly understood at this point. Accordingly, at present, for athletes who wish to do so, coffee appears to represent a useful method of caffeine ingestion around regular training, especially if they are habitual users of caffeine; for most individuals, consumption of ~3 mg/kg of caffeine (equivalent to approximately 2-3 espressos for a 60-70 kg individual) would likely be appropriate. However, the utilization of more controlled caffeine doses, requiring less liquid or concentration, may be advantageous around competitions.

Novelty Statement & Practical Applications

The findings of this review demonstrate that, whilst coffee, may, in some cases, offer similar ergogenic benefits to caffeine anhydrous (provided the caffeine dose is matched), these findings are based on a limited number of studies, with a large variability in findings. It also raises a number of practical issues regarding the use of coffee as a means of obtaining a pre-exercise dose of caffeine, including the ingestion of large amounts of liquid, variation in caffeine dose across brands, and within the same brand across time, and the consumption of a hot drink, which may affect thermoregulatory control; all of these require consideration by athlete, coach and nutritionist when determining the method of pre-exercise caffeine ingestion.

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Author Contributions

CP conceived of the idea underlying this manuscript, and authored the first draft. JG provided significant edits and writing assistance. Both authors approved the final manuscript prior to submission.

Conflicts of Interest

Craig Pickering and Jozo Grgic declare they have no conflicts of interest relevant to the content of this article.

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Study	Subjects	Habitual Caffeine Intake	Experimental Conditions	Coffee Brand	Performance Test	Outcome	Raw Performance Data
Anderson et al. (2018)	9 (7 male) experienced cyclists	316 ± 98 mg/day	Caffeinated coffee (6 mg/kg caffeine) compared to decaffeinated coffee	Starbucks VIA Ready Brew Italian Roast	30-second Wingate test	No significant effect of caffeinated coffee on peak power, mean power, and fatigue index.	*Peak power (W)* Caffeinated coffee: 942 ± 174 Decaffeinated coffee: 923 ± 168 *Mean power (W)* Caffeinated coffee: 754 ± 150 Decaffeinated coffee: 755 ± 156
Demura et al. (2007)	10 healthy young adults	Not presented	Caffeinated coffee (6 mg/kg caffeine) compared to decaffeinated coffee	Not specified	60 minutes cycle ergometer sub-maximal exercise @ 60% VO_{2max}	RPE was lower in caffeinated vs decaffeinated coffee.	N/A
Wiles et al. (1992)	18 male athletes	Not presented	3g instant coffee (~150-200mg caffeine) vs 3g decaffeinated instant coffee	Not specified	1500m time trial treadmill run	Caffeinated coffee significantly improved performance compared to decaffeinated coffee	*Time to run 1500m (sec)* Caffeinated coffee: 286 ± 32 Decaffeinated coffee: 290 ± 33
Wiles et al. (1992)	10 male athletes	Not presented	3g instant coffee (~150-200mg caffeine) vs 3g	Not specified	1100m high intensity run, with 400m	Caffeinated coffee significantly ($p < 0.05$)	*Speed of final min (km/h)* Caffeinated coffee: 24 ± 2

			decaffeinated instant coffee		"finishing burst"	improved performance compared to decaffeinated coffee	Decaffeinated coffee: 23 ± 2
Wiles et al. (1992)	6 male middle-distance athletes	Not presented	3g instant coffee (~150-200mg caffeine) vs 3g decaffeinated instant coffee	Not specified	1500m high intensity run at predetermined speed	Caffeinated coffee significantly (p < 0.025) improved performance compared to decaffeinated coffee	N/A
Clarke et al. (2018)	13 trained middle-distance runners	171 ± 250 mg/day	0.09 g/kg coffee (~3 mg/kg caffeine), decaffeinated coffee, or placebo	Nescafé Original, Nestle	Competitive one-mile run	Race time was significantly faster in the caffeinated vs decaffeinated (p = 0.018) and placebo (p = 0.006) trials.	*Race completion time (min:s.ms)* Caffeinated coffee: 04:35:37 ± 00:10:51 Decaffeinated coffee: 04:39:14 ± 00:11:21 Placebo: 04:41:00 ± 00:09:57
Marques et al. (2018)	12 well-trained adult males	Average intake of 91 mg/day	Caffeinated coffee (5.5 mg/kg caffeine) vs decaffeinated coffee	Nescafé, Nestlé.	800m running time trial	No difference in time trial performance between treatments.	*Time trial performance (min)* Caffeinated coffee: 2.39 ± 0.09 Decaffeinated coffee: 2.38 ± 0.10
Lamina and Musa (2009)	20 male young adults	Not presented	Caffeinated coffee (5, 10 and 15 mg/kg caffeine)	Capra Nescafe	20-meter shuttle run test	No significant effect of caffeine on performance	Not presented

			compared to placebo				
Church et al. (2015)	Twenty subjects (10 females)	277 ± 183 mg	Turkish coffee (providing 3 mg/kg caffeine) or decaffeinated coffee	Strauss Coffee	5km running time trial, reaction to visual stimuli tests, and object tracking	Upper body reaction performance was significantly higher in the caffeinated vs decaffeinated coffee trials. No differences were reported in other performance tests.	*Time trial performance (seconds)* Caffeinated coffee: 1685 ± 217 Decaffeinated coffee: 1717 ± 256
Graham et al. (1998)	9 (8 male) young adult (21-47 y) trained endurance runners	One participant with no caffeine intake, two “light” users (<100 mg/day) and the reaming were “moderate” users (<500 mg/day)	4.45 mg/kg, as either caffeine capsules, caffeinated coffee, or decaffeinated coffee + caffeine	Not specified	5 treadmill trials to exhaustion @ 85% VO_{2max}	Caffeine capsule ingested significantly enhanced endurance performance compared to other trials.	*Total running time (min)* Decaffeinated coffee: 34 ± 12 Decaffeinated coffee + caffeine: 34 ± 11 Caffeinated coffee: 34 ± 12 Placebo: 30 ± 12 Caffeine: 40 ± 12
Richardson & Clarke (2016)	9 resistance trained males	241 ± 122 mg	Caffeinated coffee (0.15 g/kg; ~5 mg/kg caffeine),	Nescafé Original coffee	Squat and bench press repetitions to	Caffeinated coffee enhanced performance	*Bench press (repetitions)*

			caffeine (5 mg/kg), caffeine (5 mg/kg) + decaffeinated coffee, and decaffeinated coffee		failure @ 60% 1RM	compared to placebo, but not compared to decaffeinated coffee. Decaffeinated coffee and caffeine consumed in combination significantly enhanced performance compared to decaffeinated coffee, placebo, and caffeine alone.	Caffeinated coffee: 13 ± 2 Caffeine: 13 ± 2 Decaffeinated coffee + caffeine: 12 ± 3 Decaffeinated coffee: 12 ± 2 Placebo: 12 ± 2 *Squat (repetitions)* Caffeinated coffee: 17 ± 5 Caffeine: 15 ± 5 Decaffeinated coffee + caffeine: 18 ± 5 Decaffeinated coffee: 14 ± 5 Placebo: 13 ± 4
Hodgson et al. (2013)	8 trained male cyclists/triathletes	≤300 mg	Caffeine (5 mg/kg), compared to caffeinated coffee (providing 5 mg/kg caffeine), decaffeinated coffee, and placebo.	Nescafé Original coffee	30 minutes steady state cycling, followed by 45-minute time trial	Performance in the time trial was significantly faster for both caffeine and caffeinated coffee trials compared to decaffeinated coffee and placebo, with no real difference	*Time trial finishing time (min)* Caffeine: 38 ± 1 Caffeinated coffee: 38 ± 2 Decaffeinated coffee: 40 ± 2 Placebo: 40 ± 1 *Mean power output (W)* Caffeine: 294 ± 17 Caffeinated coffee: 291 ± 20

						between the two.	Decaffeinated coffee: 276 ± 20 Placebo: 277 ± 11
Clarke et al. (2016)	12 recreationally active males	Not presented	Caffeine (3 mg/kg) compared to coffee (providing 3 mg/kg caffeine), placebo, and control	Nescafé Original coffee	18 x 4-second cycle ergometer sprints	No significant differences in peak or mean power output, or RPE, between all experimental conditions.	*Peak power (W)* Caffeinated coffee: 949 ± 174 Placebo: 971 ± 149 Caffeine: 949 ± 199 Control: 975 ± 170 *Mean power (W)* Caffeinated coffee: 862 ± 44 Placebo: 887 ± 119 Caffeine: 873 ± 172 Control: 892 ± 143

Table 1 - Studies comparing caffeinated coffee compared to placebo/decaffeinated coffee; VO_{2max} maximum oxygen uptake; RPE rating of perceived exertion, 1RM one-repetition maximum.

Study	Subjects	Habitual caffeine intake	Experimental Conditions	Coffee Brand	Performance Test	Outcome	Raw Performance Data
Graham et al. (1998)	9 (8 male) young adult (21-47 y) trained endurance runners	One participant with no caffeine intake, two "light" users (<100 mg/day) and the reaming were "moderate" users (<500 mg/day)	4.45 mg/kg, as either caffeine capsules, caffeinated coffee, or decaffeinated coffee + caffeine	Not specified	5 treadmill trials to exhaustion @ 85% VO_{2max}	Caffeine capsule ingested significantly enhanced endurance performance compared to other trials.	*Total running time (min)* Decaffeinated coffee: 34 ± 12 Decaffeinated coffee + caffeine: 34 ± 11 Caffeinated coffee: 34 ± 12 Placebo: 30 ± 12 Caffeine: 40 ± 12
Trexler et al. (2016)	54 resistance trained males	33 ± 60 mg	300 mg caffeine (3-5 mg/kg) compared to 8.9g coffee (303 mg caffeine) and placebo.	Nescafé House Blend	1 RM and repetitions to fatigue @ 80% 1RM on bench press and leg press, alongside 5 x 10-second cycle ergometer sprints	No beneficial effect of coffee or caffeine on strength performance, and no difference between the two, except for leg press 1RM, where coffee outperformed caffeine, but not placebo. Total work in	*Leg press 1RM (kg) pre* Caffeine: 284 ± 63 Coffee: 309 ± 86 Placebo: 279 ± 69 *Leg press 1RM (kg) post* Caffeine: 291 ± 64 Coffee: 324 ± 86 Placebo: 293 ± 68 *Bench press 1RM (kg) pre* Caffeine: 93 ± 19 Coffee: 96 ± 18 Placebo: 87 ± 17

						the sprint test decreased with placebo ingestion, but not with caffeine or coffee.	*Bench press 1RM (kg) post* Caffeine: 95 ± 19 Coffee: 97 ± 18 Placebo: 89 ± 17
Richardson & Clarke (2016)	9 resistance trained males	241 ± 122 mg	Caffeinated coffee (0.15 g/kg; ~5 mg/kg caffeine), caffeine (5 mg/kg), caffeine (5 mg/kg) + decaffeinated coffee, and decaffeinated coffee	Nescafé Original coffee	Squat and bench press repetitions to failure @ 60% 1RM	Caffeinated coffee enhanced performance compared to placebo, but not compared to decaffeinated coffee. Decaffeinated coffee and caffeine consumed in combination significantly enhanced performance compared to decaffeinated coffee, placebo, and caffeine alone.	*Bench press (repetitions)* Caffeinated coffee: 13 ± 2 Caffeine: 13 ± 2 Decaffeinated coffee + caffeine: 12 ± 3 Decaffeinated coffee: 12 ± 2 Placebo: 12 ± 2 *Squat (repetitions)* Caffeinated coffee: 17 ± 5 Caffeine: 15 ± 5 Decaffeinated coffee + caffeine: 18 ± 5 Decaffeinated coffee: 14 ± 5 Placebo: 13 ± 4
Hodgson et al. (2013)	8 trained male cyclists/triathletes	≤300 mg	Caffeine (5 mg/kg), compared	Nescafé Original coffee	30 minutes steady state	Performance in the time trial	*Time trial finishing time (min)*

			to caffeinated coffee (providing 5 mg/kg caffeine), decaffeinated coffee, and placebo.		cycling, followed by 45-minute time trial	was significantly faster for both caffeine and caffeinated coffee trials compared to decaffeinated coffee and placebo, with no real difference between the two.	Caffeine: 38 ± 1 Caffeinated coffee: 38 ± 2 Decaffeinated coffee: 40 ± 2 Placebo: 40 ± 1 *Mean power output (W)* Caffeine: 294 ± 17 Caffeinated coffee: 291 ± 20 Decaffeinated coffee: 276 ± 20 Placebo: 277 ± 11
Clarke et al. (2016)	12 recreationally active males	Not presented	Caffeine (3 mg/kg) compared to coffee (providing 3 mg/kg caffeine), placebo, and control	Nescafé Original coffee	18 x 4-second cycle ergometer sprints	No significant differences in peak or mean power output, or RPE, between all experimental conditions.	*Peak power (W)* Caffeinated coffee: 949 ± 174 Placebo: 971 ± 149 Caffeine: 949 ± 199 Control: 975 ± 170 *Mean power (W)* Caffeinated coffee: 862 ± 44 Placebo: 887 ± 119 Caffeine: 873 ± 172 Control: 892 ± 143

Table 2 - Studies comparing caffeine with caffeinated coffee; RPE rating of perceived exertion; 1RM one-repetition maximum; VO_{2max} maximum oxygen uptake.

Study	Subjects	Habitual caffeine intake	Experimental Conditions	Coffee Brand	Performance Test	Outcome	Raw Performance Data
Butts & Crowell (1985)	28 active subjects (15 female)	Not presented	300 mg caffeine + decaffeinated coffee, compared to decaffeinated coffee	Not specified	Time to exhaustion cycle ergometer test @ ~75% Vo_{2max}	Caffeine increased time to exhaustion, although these changes were not significant	*Time of exercise (min)* *Females* Caffeine + decaffeinated coffee: 69 ± 23 Decaffeinated coffee: 60 ± 27 *Males* Caffeine + decaffeinated coffee: 70 ± 32 Decaffeinated coffee: 68 ± 33
Graham et al. (1998)	9 (8 male) young adult (21-47 y) trained endurance runners	One participant with no caffeine intake, two “light” users (<100 mg/day) and the reaming were “moderate” users (<500 mg/day)	4.45 mg/kg, as either caffeine capsules, caffeinated coffee, or decaffeinated coffee + caffeine	Not specified	5 treadmill trials to exhaustion @ 85% VO_{2max}	Caffeine capsule ingested significantly enhanced endurance performance compared to other trials.	*Total running time (min)* Decaffeinated coffee: 34 ± 12 Decaffeinated coffee + caffeine: 34 ± 11 Caffeinated coffee: 34 ± 12 Placebo: 30 ± 12 Caffeine: 40 ± 12

Richardson & Clarke (2016)	9 resistance trained males	241 ± 122 mg	Caffeinated coffee (0.15 g/kg; ~5 mg/kg caffeine), caffeine (5 mg/kg), caffeine (5 mg/kg) + decaffeinated coffee, and decaffeinated coffee	Nescafé Original coffee	Squat and bench press repetitions to failure @ 60% 1RM	Caffeinated coffee enhanced performance compared to placebo, but not compared to decaffeinated coffee. Decaffeinated coffee and caffeine consumed in combination significantly enhanced performance compared to decaffeinated coffee, placebo, and caffeine alone.	*Bench press (repetitions)* Caffeinated coffee: 13 ± 2 Caffeine: 13 ± 2 Decaffeinated coffee + caffeine: 12 ± 3 Decaffeinated coffee: 12 ± 2 Placebo: 12 ± 2 *Squat (repetitions)* Caffeinated coffee: 17 ± 5 Caffeine: 15 ± 5 Decaffeinated coffee + caffeine: 18 ± 5 Decaffeinated coffee: 14 ± 5 Placebo: 13 ± 4
McLellan and Bell (2004)	13 subjects (9 male)	608 ± 446 mg	Decaffeinated coffee + placebo, decaffeinated coffee + caffeine (5 mg/kg), coffee (1.1 mg/kg caffeine) + caffeine (5 mg/kg), coffee +	Royal Blend	Cycle ergometer time to exhaustion @ 80% VO_{2max}	Prior consumption of coffee did not reduce the subsequent ergogenic effect of anhydrous caffeine.	*Time to exhaustion (min)* Decaffeinated coffee + placebo: 22 ± 8 Decaffeinated coffee + caffeine (5 mg/kg): 29 ± 7

			caffeine (3 mg/kg), coffee + caffeine (7 mg/kg), placebo + caffeine (5 mg/kg).				Coffee (1.1 mg/kg caffeine) + caffeine (5 mg/kg): 28 ± 11 Coffee + caffeine (3 mg/kg): 25 ± 8 Coffee + caffeine (7 mg/kg): 26 ± 8 Placebo + caffeine (5 mg/kg): 27 ± 8
Trice and Haymes (1995)	8 trained male subjects	Non regular caffeine users	5 g decaffeinated coffee + 5 mg/kg caffeine, compared to 7g decaffeinated coffee	Sanka	3 x 30-min cycle ergometer trials @ 70 rpm	Time to exhaustion was significantly longer in the caffeine compared to no caffeine trial	*Time to exhaustion (min)* Caffeine + decaffeinated coffee: 78 ± 15 Decaffeinated coffee: 61 ± 6
Costill et al. (1978)	9 competitive cyclists (7 males)	Not presented	Coffee + 330 mg caffeine anhydrous, compared to decaffeinated coffee	Not specified	Cycle ergometer time to exhaustion task @ 80% VO_{2max}	Subjects were able to perform significantly more work in the caffeine vs decaffeinated coffee trial	*Time to exhaustion (min)* Caffeine + decaffeinated coffee: 90 ± 22 Decaffeinated coffee: 76 ± 15

Table 3 – Studies comparing the ergogenic effects of caffeine added to decaffeinated coffee, compared to decaffeinated coffee alone, or placebo; VO_{2max} maximum oxygen uptake; 1RM one-repetition maximum