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Caffeine Supplementation as an Ergogenic Aid for Muscular Strength and Endurance: A Recommendation for Coaches and Athletes

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Abstract

Caffeine (1, 3, 7-trimethylxanthine) which can be ubiquitously found in energy drinks, sodas, coffee, and supplements, is one of the principal legal drugs consumed worldwide. Caffeine based ergogenic aids are utilized prolifically within training and competition for an ergogenic benefit to enhance sporting performance by both recreational and elite athletes. The evidence of caffeine's ability to enhance endurance performance is well established, however, evidence of an ergogenic benefit for muscular endurance and strength-based tasks is limited. Moreover, the limited evidence for caffeine's ergogenic benefit in muscular endurance and strength is equivocal, and therefore, practical recommendations for the implementation of caffeine supplementation in training and competition for coaches, and practitioners is difficult. Indeed, it is currently not known if, and how caffeine may improve muscular endurance and/or strength based tasks. Variability in the findings could be due to several factors including muscles tested, participant characteristics, exercise protocol, type and dose of caffeine used. This brief review will discuss the current literature relating to the potential efficacy of caffeine to enhance muscular endurance and strength based performance, and provides evidence based recommendations for athletes and coaches to implement.

Keywords

Resistance training; Strength; Endurance; Supplementation; Coffee; Energy drinks

Introduction

Caffeine is a plant alkaloid found in tea, coffee, soft drinks, cocoa and more recently, energy drinks. As a result of its removal from the World Anti-Doping Agency's (WADA) list of prohibited substances in 2004, it is now one of the highest used legal drugs worldwide with 74% of elite athletes consuming caffeine prior to competition [1]. In addition to, and perhaps a consequence of, this rise in professional use, non-elite athletes are becoming consistent users of caffeine in an attempt to aid recreational performance [2]. This has promoted an increase in the sale of caffeine based supplements and energy drinks [3] and these readily available forms of the drug are now typically consumed by younger populations and even those not participating in sport or exercise [4].

In a sport and exercise context, caffeine has been consistently shown to aid a variety of endurance based tasks [5-7] with significant enhancements in cycling [8,9], swimming [10] and rowing [11] performance all being reported. On the other hand, both supporting [12-18] and contradicting [19-23] research has been published in terms of muscular endurance. Furthermore, the evidence of caffeine improving muscular strength is a concept that produces additional equivocal conclusions. Few studies have reported increases in one repetition maximum (1RM) post caffeine supplementation in comparison to placebo [21,23] and control [24] trial with a superior number reporting no change [20,25,26].

Caffeine's primary mechanistic process likely occurs through the antagonising of adenosine [27]. This process is achieved by caffeine binding to adenosine receptors, reducing adenosine's ability to slow neural activity, reduce arousal, and induce sleep [28]. Further rewards from caffeine's effect on adenosine receptors include enhanced neurotransmitter release, increased firing rates, and amplified spontaneous and evoked potentials [29]. Caffeine has also been shown to alter metabolic substrate utilization [9] and provide enhanced fat oxidation and consequential glycogen sparing [30]. Alterations to pain perception following caffeine supplementation have also been reported [31] most likely due to enhanced secretion of β-endorphins [32]. More specifically to strength performance, possible mechanisms also include increased muscle activation [33], motor unit recruitment [34], and enhanced excitation contraction coupling [35].

It should be noted, that it is beyond the scope of this review to provide a comprehensive overview of the mechanisms of caffeine. The primary purpose of this review is to provide in depth analysis of the evidence relating to the use of caffeine in muscular endurance and strength based exercise, and provide coaches and athletes, at both elite and recreational level, with recommendations for the use of caffeine with regards to muscular strength and muscular endurance. For a complementary, wider-ranged review of all current literature, readers is direct to other published review articles [36,37] and a meta-analysis [38].

Caffeine and muscular endurance

Several studies have investigated the effects of caffeine on muscular endurance performance using a variety of protocols [12-23,26,39-41](Table 1). Caffeine's ability to increase the amount of repetitions performed at set percentages of participants 1 RM is an area that has been relatively well explored [13-23,26,39,40]. In 2011, Astorino et al. [40] recruited fourteen resistance trained, average caffeine (~218 mg/day) consuming males to perform resistance exercises to failure. Participants consumed either caffeine (6 mg.kg.bw^{-1}) or a placebo one week apart in a double blind randomized repeated measures cross over design. One hour post ingestion of either supplement, participants were required to perform four sets of barbell bench press, leg press, bilateral row, and barbell shoulder press to fatigue at 70-80% 1 RM. Total weight lifted and number of repetitions were recorded

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Table 1: Summary of studies for muscular endurance.

Study	Protocol	Participants	Habitual Caffeine	Dose	Performance Increase
Astorino et al.	4 sets of BP, SP at 70% 1 RM and , LP BR and 80% 1 RM Number of reps performed	14 resistance-trained men	218 mg per day with a range of 120-500 mg per day	6 mg.kg.bw^{-1}	Increase in LP reps
Duncan et al.	RTF: BP, DL, PR, BS at 60% 1RM.	13 resistance-trained men	211 mg with a range of 120–400 mg per day.	Energy drink: 179 mg caffeine with vitamins B3, B6, B9, and B12; tyrosine; taurine; malic acid; and glucuronolactone	Increased combined RTF Decreased RPE Increased RTIME and RTIPE
Duncan et al.	RTF: BP, DL, PR, BS at 60% 1RM.	11 resistance trained (9 males, 2 females)	67.4 mg/day with a range of 120-400 mg/day	5 mg.kg.bw^{-1}	Increase in combined RTF
Hudson et al.	4 sets of LE, AC at predetermined 12 rep max. Total reps performed. repetitions to failure RPE, Pain.	15 males	~100-400 mg per day	6-6.4 mg.kg.bw^{-1}	Increase in LE Non Sig increase in AC
Richardson and Clarke	RTF: BS, BP at 60% 1 RM.	9 resistance trained males	241 ± 122 per day	Coffee: 433 mg (±40 mg) Decaf coffee: 2 mg (±0 mg) Decaf with caffeine: 425 mg (±39 mg) Caffeine: 425 mg (±39 mg)	More RTF for Decaf with caffeine and Coffee than Caffeine and Decaf.

BP=Bench Press, LP=Leg Press, BR=Bilateral Row, SP=Shoulder Press, DL=Dead Lift, PR=Prone Row, BS=Back Squat, AC=Arm Curl, LE=Leg Extension, RTF= Repetitions to Failure, 1 RM= One repetition maximum, RPE=Rating of Perceived Exertion, RTIME=Readiness to Invest in Mental Effort, RTIPE= Readiness to Invest in Physical Effort

and analysed using a two-way analysis of variance with repeated measures to examine differences across trials and sets. Compared to the placebo, caffeine provided a small, and marginally significant (p=0.047) increase in repetitions performed in the leg press exercise, but provided no benefit to any of the upper body exercises. On average, participants performed 1.5 repetitions more in sets one and two of the leg press exercise post caffeine consumption. Although mean total weight lifted between trials was similar (caffeine: 22,409.5 ± 3,773.2 kg *vs.* placebo: 21,185.7 ± 4,655.4 kg), the researchers identified nine 'responders' to caffeine based on meaningful increases (7.2%) in total weight lifted across exercises. They concluded that although caffeine provided a significant increase (albeit marginal) within this protocol, further work needed to be performed to fully elucidate individual differences (i.e. responders *vs.* non-responders) in response to caffeine. Da Silva et al. [15] employed a similar protocol in which participants performed three sets of both bench press and leg press at 80% of their relative 1 RM. Fourteen moderately resistance trained, average (~200 mg/day) caffeine consuming males were recruited to consume both caffeine (5 mg.kg.bw^{-1}) and placebo one hour prior to exercise in a randomized counter balanced repeated measures design. Total repetitions performed increased by 11.60% (Placebo: 26.86 ± 1.74; Caffeine: 30.00 ± 1.87; p=0.027) and 19.10% (Placebo: 40.0 ± 4.22; Caffeine: 47.64 ± 4.69; p=0.009) for the bench press and leg press exercises respectively. Similar to Astorino et al., caffeine's effect on upper body exercise was less than that employed on lower body exercise, however, in this study, contrary to Astorino's findings, both increased significantly. This discrepancy between upper and lower body responses to caffeine has been previously reported by Hudson et al. [18]. Fifteen resistance trained, male, moderate (100-400 mg/day) caffeine consumers were recruited to perform four sets of leg extensions and arm curls at a predetermined intensity of 12 repetition maximum. Caffeine (6-6.4 mg.kg.bw^{-1}), aspirin (10-10.4 mg.kg.bw^{-1}) and a placebo were ingested in a randomized manner one hour prior to the exercise. Results indicated that a significantly greater amount of repetitions were performed on the leg extension exercise in the presence of caffeine, yet no significant increase was observed in the arm curls. At a similar intensity (70-80% 1 RM) to the aforementioned studies, no ergogenic benefit of caffeine has been reported for both lower body [20,22] and upper and lower body [23] exercises in resistance trained males. Therefore, in addition to differences in the muscles being tested, it is also important to highlight differences in the doses used (i.e. 5 mg, 6 mg, 6-6.4 mg), and the effect of responders *vs.* non-responders (i.e. those more habituated to caffeine), which could explain some of the variation in the findings, and makes the comparison of studies problematic.

At a slightly lower intensity, the discrepancy between upper and lower body responses has been more recently supported by work from Richardson and Clarke [39] where nine resistance trained males performed repetitions to failure at 60% of their relative 1 RM for both squat and bench press exercises. Participants consumed caffeine, coffee, decaf coffee or decaf coffee with caffeine. Attempts were made to ensure the caffeine containing groups yielded 5 mg.kg.bw^{-1} and absolute values were reported as coffee: 433 mg, decaf coffee: 2 mg, decaf with caffeine: 425 mg and caffeine: 425 mg. Participants were able to perform significantly more repetitions for the squat exercise in the presence of caffeine when consumed as decaf plus caffeine (18 ± 5) and coffee (17 ± 5) compared to decaf coffee (14 ± 5), caffeine

(15 ± 5) and placebo (13 ± 4). No change in bench press however was seen following consumption of any aforementioned supplements. One possible explanation for these findings may be due to voluntary muscle activation. Voluntary muscle activation is less in larger muscle groups (knee extensors), compared to smaller muscle groups (shoulder flexors) [38]. Caffeine may likely act via central nervous system activation, and therefore, its capacity to enhance motor unit recruitment and/or motor unit firing rate should be greater in the larger muscle groups [38]. Moreover, the larger lower body muscles may be more sensitive to caffeine compared to the smaller upper body muscles potentially due to an increase in the number of adenosine receptors due to larger muscle size [40-42].

Conversely, Trexler et al. [17] recruited fifty-four, low caffeine consuming (32.9 ± 59.6 mg/day) resistance trained males to perform leg press and bench press exercises at 60% 1 RM. Participants' number of repetitions were recorded pre and thirty minutes post either caffeine (300 mg; yielding 3-5 mg.kg.bw^{-1}), coffee (8.9 g; 303 mg.kg. bw^{-1}) or placebo ingestion. Although performance increased in the second test in all conditions, there was no effect of caffeine or coffee on repetitions performed by the participants for either exercise, when compared to placebo. The conflicting findings reported in this study compared to previous studies in terms of lower body exercise may be due to either the shorter time period between ingestion and exercise (thirty minutes as opposed to the commonly used one hour) or alternatively the power of a caffeine related placebo, which has been previously identified [24,43]. Participants may have performed better in the second test if they believed they had ingested the caffeine.

The effect of caffeine on muscular endurance at 60% 1 RM was also investigated by Duncan et al. [16]. To measure the effect of a caffeine containing energy drink (179 mg caffeine with vitamins B3, B6, B9, and B12; tyrosine; taurine; malic acid; and glucuronolactone) on muscular endurance, participants were required to perform one set of bench press, deadlift, prone row, and back squat to failure, one hour after consuming either the energy drink or a placebo. Although no significant changes were identified between individual exercises, total repetitions performed when all exercises were combined, and averaged, were significantly higher in the caffeine (20.1 ± 6.3) condition compared to the placebo (18.6 ± 5.6) with average mean difference of 1.39 repetitions. These results obtained following energy drink consumption have also been replicated following caffeine ingestion (5 mg.kg.bw^{-1}) prior to a similar protocol in both an all-male [14] and a mixed gender [13] population. In contrast to both of Duncan et al. studies showing a beneficial effect of caffeine on muscular performance at 60% 1 RM, no increase in performance was observed in resistance trained males performing bench press and leg press [26] or bench press only, following a caffeine (300 mg) mouth rinse at the same percentage of 1 RM. However, the lack of a significant effect in the latter study [25] is most likely due to the method of caffeine administration (i.e. mouth rinse) compared to the traditional administration of caffeine (i.e. ingestion) utilised in all other studies. Nevertheless, mouth rinsing is a relatively new area of research that warrants further investigation.

In addition to the equivocal findings of the aforementioned studies, which as discussed may be due to several factors including participant characteristics, dose, type and timing of caffeine, exercise protocol, intensity, and muscles mass, there is also one large area of research that is clearly lacking. The use of caffeine to enhance muscular endurance in females is vastly limited. Only one of the aforementioned studies [13] used female participants in their sample, and even then the number of females included was very small (n=2). The only other recent study [21] that has investigated the effected of caffeine on muscular endurance in females (n=15), showed no significant effect of caffeine (6 mg.kg.bw^{-1}) on number of repetitions performed at 60% 1 RM in the bench press (p=0.81) despite an increase in muscle strength (see muscle strength section below). The authors of this study reported large differences in caffeine habituation and emotional responses to caffeine from the female participants. Those females who reported the largest emotional responses, performed more repetitions during the 60% 1 RM bench press exercise, demonstrating that there may have been ‘responders’, and ‘non-responders’ in this study, which could account for the overall non-significant finding.

Gender differences in the response to caffeine may also exist between males and females, and therefore the results above may not be generalizable to females (athletes or non-athletes). Despite there being no studies that have directly compared the effects of caffeine on responses to muscular endurance between males and females, there have been limited studies that have compared caffeine responses between males and females in general, which could offer some insight into the potential differences that could be expected during muscular endurance. Females in the mid follicular phase of their menstrual cycle demonstrate similar pharmacokinetics of caffeine to males. The effect of estrogen on caffeine metabolism is also evident. The clearance of caffeine in women has been shown to slow near the end of the luteal phase [44], in the presence of estrogen-containing birth control [45] or as a result of estrogen replacement therapy in post-menopausal women [46]. However, females have a higher peak plasma level of caffeine and it remains elevated for longer compared to males [47]. Additionally, the hemodynamic responses to caffeine are different in males and females [45]. Females showed an increase in stroke volume and cardiac output with no difference in vascular resistance, whereas males showed no difference in cardiac output but increases in vascular resistance. Furthermore, females may have more adenosine receptors on adipocytes and therefore, may be more responsive to the effects of caffeine on adipocyte lipolysis. However, in general males have a greater catecholamine response to stress, and as caffeine increases catecholamine activity there may be gender differences in the mechanisms and effectiveness of caffeine between males and females, although this requires further study. Moreover, how these physiological differences may impact the effectiveness of caffeine on muscular endurance, remains to be elucidated (Table 1).

Caffeine and Muscular Strength

The association between caffeine ingestion and strength performance is an area that currently lacks robust scientific evidence; however, there is limited evidence that caffeine may enhance strength performance (Tables 2 and 3). For example, fifteen resistance trained females performed bench press 1 RM tests following caffeine (6 mg.kg. bw^{-1}) or placebo ingestion [21]. Results revealed a significant increase in bench press 1 RM scores following caffeine (52.9 ± 11.1) compared to a blinded placebo (52.1 ± 11.7). However, as aforementioned the effect of caffeine on performance in females is limited. Nevertheless, this study suggests that caffeine may be a potential ergogenic aid that can offer positive effects on upper body strength in females. Further research is required to confirm these findings, and examine different muscles. Beck et al. [23] revealed a similar increase of 2.1% in a controlled study with thirty-seven resistance-trained males. However, within this study, participants did not show a response to caffeine with regards to leg extension 1 RM, which is the opposite of the evidence found for muscular endurance. More interestingly, in both the aforementioned experiments, participant's repetitions to failure at 60% 1 RM did not improve following ingestion of caffeine suggesting that the mechanisms for the efficacy of caffeine may differ depending on the exercise task (i.e. endurance *vs.* strength). No study to date has investigated this phenomenon, and therefore, the mechanisms responsible for caffeine's effect on strength and endurance remain to be elucidated.

In contrast to these two studies, a plethora of research suggests no benefit of caffeine on bench press [17,20,22,25,26], leg extension [25], leg press [17,26] and latissimus pull down [20] 1 RM. However, all but one of these studies also measured repetitions to failure within the protocol and found no ergogenic effect, even at ranges previously supported by other research (60-80% 1 RM) in the previous section. It would be unlikely that the majority of these participants were 'non responders' and therefore, this suggests that other factors could account for such variation in findings.

One possible variation in methodology that could alter the response to caffeine may be the dose ingested. Work by Archna and Jaspal [12] investigated the importance of different caffeine dosages. Four incremental dosages (0,5,9 and 13 mg.kg.bw^{-1}) were ingested by thirty-one healthy individuals and it was reported that all conditions improved measures of muscular endurance and fatigue index. Only the highest value (13 mg.kg.bw^{-1}) however produced a significant effect on muscular strength. This discovery may therefore explain the lack of statistical change observed in the majority of experiments as the dosages administered fall way below this value (2-6 mg.kg.bw^{-1}). This does not however explain the increase shown in the studies where values of 6 mg.kg.bw^{-1} [21] and 201 mg (BW=83.6 yielding; 2.4 mg.kg.bw^{-1}) [23] were administered.

Another possible explanation may be the habitual caffeine intake of participants and the consequential tolerance to caffeine administration. Unfortunately, in the two articles displaying a significant effect of caffeine on strength, the habitual caffeine use of the participants was not reported. In studies reporting no change, two of the five studies reported caffeine use and revealed mean values of 110 mg [26] and 32.9 mg [17] which were deemed as low-moderate use, making caffeine tolerance an unlikely cause. On the contrary, high habitual caffeine users when participating in such research will be restricted from consuming caffeine prior to testing. Caffeine withdrawal symptoms have been well documented [48] and would be sufficient to cause a decrease in performance in the placebo condition, even though some of these symptoms may have been alleviated [49].

A final variable that has been identified as a possible cause is training status. This theory was tested in work by Brooks et al in 2015 [24] where seven untrained and seven resistance trained individuals were recruited to perform 1 RM squats post ingestion of caffeine or a masked placebo (Table 2). It was reported that the trained individuals showed a non-significant increase of 2.9 kg and 2.1 kg for the caffeine and placebo trails respectively, when compared to a control. In untrained individuals however, a significantly greater amount of weight was lifted within both the caffeine (102.8 ± 24.1 kg) and placebo (100.7 ± 24.2 kg) trials when compared to the control (92.1 ± 27.9 kg). It was concluded by the authors that although a slight ergogenic effect of caffeine may exist in terms of strength performance, a large proportion of this change may be due to placebo effects, and expectancy in increased performance. It was also suggested that untrained individuals may possess enhanced expectancy and susceptibility to placebo effects therefore explaining the variation between the trained and untrained populations. Further analyses of the previously mentioned studies that reported no change in 1 RM measurements, shows that these studies were all comparing caffeine to a blinded placebo. Furthermore, although no significant change was reported, mean increases of 1.5 kg in bench press [26], 2.5 kg in leg press [25], 7.4 kg in latissimus dorsi pull down [20] and 2.1 kg in squats [24] have even been shown in comparison to a masked placebo. The individual differences and concept of responders and non-responders may in fact be the key factors in statistical significance being revealed in these experiments, and possibly masking a worthwhile change in performance for some participants. Therefore, future research should focus on the psychological effects of 'expectancy' and 'belief', and the potential of 'responders' *vs.* 'non-responders', whilst ensuring these studies are ecologically valid (i.e. performed in a real world setting), in order to allow such findings to be generalised to the wider athletic population (Tables 2 and 3).

Practical Recommendations

Despite caffeine consistently demonstrating a positive effect during endurance based tasks the mechanisms responsible for such ergogenic benefit only appear to offer a positive effect during very specific muscular endurance tasks, for example, when resistance exercise is performed at lower intensities (~60% 1RM). This advantage does however appear to deteriorate when maximal, or near maximal; strength performance is performed, with the body of evidence suggesting that caffeine does not improve muscular strength. Nevertheless, there are several limitations that exist within the current research, which may account for the lack of evidence for caffeine and strength based exercise. Subsequently, future research should focus on the mechanism(s) responsible for caffeine's improvement in strength, and the individual responses.

The efficacy of caffeine supplementation does appear to vary based on exercise type. More consistent, favourable adaptations appear to occur at lower intensities (i.e. 60% 1RM) and for a still unknown reason, also more predominantly in lower body exercise. Encouraging results have also been reported at slightly higher intensities, and for upper body exercise, but the apparent disparity between upper and lower body exercise requires further research. In terms of muscular strength the only reported increases of statistical significance have both occurred during bench press exercise [21,23] for both males and females. Furthermore, as the vast majority of studies have been conducted in males, caution should be taken when generalising these findings to females, as differences in caffeine metabolism, and its effects on performance between males and females are likely.

It is therefore suggested that caffeine recommendations should be determined by the exercise mode being performed. For athletes

Table 2: Summary of studies for muscular strength.

Study	Protocol	Participants	Habitual Caffeine	Dose	Performance Increase
Brooks et al.	1RM BS, force production, muscle activation	7 trained 7 untrained Males	Not mentioned	5 mg.kg. bw^{-1}	Untrained increase 1 RM for CAF and PLA
Hendrix et al.	1 RM: BP and LE	21 untrained men	Not Mentioned	400 mg	No change

1 RM= One repetition maximum, BP=Bench Press, BS=Back Squat, LE=Leg Extension.

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Table 3: Summary of studies for muscular strength and endurance.

Study	Protocol	Participants	Habitual Caffeine	Dose	Performance Increase
Astorino et al.	1RM: BP, LP RTF: BP, LP at 60% 1 RM	22 resistance-trained males	110mg per day (range of 0-600)	6 mg.kg.bw^{-1}	None significant 11% and 12% increases in RTF for BP and LP
Beck et al.	1RM LE and BP RTF: LE and BP at 80% 1RM Wingate Anaerobic Tests	37 resistance-trained men	Not Mentioned	201 mg.	Increase in BP 1 RM
Clarke et al.	1RM: BP RTF: BP at 60% 1 RM Arousal and RPE	15 recreationally resistance-trained males	Not Mentioned	10 second mouth rinse 300 mg CAF 300mg CAF 15g CHO	Increase in felt arousal
Eckerson et al.	1RM BP RTF: BP at 70% 1RM	17 physically active males	Not Mentioned	500 ml of sugar-free Red Bull containing 160 mg Caffeine, taurine (2000 mg), and glucunorolactone (1200 mg) 500 ml of a sugar-free drink containing caffeine only (160 mg) 500 ml of a sugar-free CAF-free	None
Goldstein et al.	1RM BP RTF: BP at 60% 1 RM	15 Resistance trained women	Not Mentioned	6 mg.kg.bw^{-1}	Increase in 1RM
Trexler et al.	1RM: BP, LP RTF: BP, LP at 60% 1RM	54 resistance-trained males	32.9 ± 59.6 mg/day	CAF:300 mg COFFEE: 303 mg caffeine	None
Williams et al.	1 RM: BP, LPD RTF: BP, LPD at 80% 1RM 30-second Wingate test	9 resistance trained males	45-68 mg (on day prior to visit)	300 mg 300 mg + 60 mg Ephedra	None

BP=Bench Press, LP=Leg Press, LE=Leg Extension, LPD=Latissimus Pull Down, RTF= Repetitions to Failure, 1 RM= One repetition maximum, RPE=Rating of Perceived Exertion

performing muscular endurance based tasks between 60-80% 1 RM, the effects of caffeine supplementation seem to be of benefit. For recreational gym users, competitive bodybuilders, and athletes attempting to increase lean muscle mass, the recommended resistance training intensity falls within this range [50] and could therefore be recommended for increased performance and consequential hypertrophy. For athletes and those participating in maximal resistance work the recommendation is ambiguous. The evidence of increased bench press 1 RM in highly resistance trained individuals will be of interest to this population, and more specifically to competitive power lifting athletes who perform the bench press as a compulsory lift. Furthermore, the non-significant increases also being reported in various other movements should also gain attention from these athletes. At a competitive level, an increase of 1-2% in a maximal lift is often the difference between success and failure and changes of this magnitude have been regularly reported. Therefore, despite 'mean changes' not being statistically significant in these reported studies, there were participants that demonstrated meaningful increases in their performances, which cannot be ignored.

Should caffeine supplementation be of interest, it is apparent that the supplement should be consumed at a dosage of 3-6 mg.kg.bw^{-1} one hour prior to exercise or competition as a minimum. Dosage as high as 13 mg.kg.bw^{-1} may offer greater benefits, however, adverse effects of the drug are more likely, and therefore such doses such be used with caution. It may be of further recommendation to begin with a lower dosage and slowly increase the amount administrated in order to avoid both adverse effects, and accelerated caffeine tolerance. If correct administration is achieved, and the consumer is of high response, then increases in both muscular endurance and muscular strength may be observed. In terms of muscular endurance increases of 1-5 repetitions may be observed per set to failure. This value would likely be towards the lower end of the range for upper body exercise and on the higher end for lower body. With regards to muscular

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strength it would not be unexpected to observe increases of 1-3% in one repetition maximum scores depending on the responsiveness of the athlete.

The determination of reliable evidence based recommendation for the use of caffeine in muscle endurance and strength is currently not possible due to the equivocal findings. Subsequently, at present, we cannot promote, nor discourage, the use of caffeine by athletes or coaches in muscle strength and endurance based exercise. Based on the evidence provided in this review, as well as their own experiences and practices, athletes and coaches should use caffeine within the safe recommended dose, and on an individual case-by-case basis. Future research is required in order to establish if there is any ergogenic benefit, and the mechanisms responsible for this, in order to provide evidenced based practical recommendations across various muscular endurance and strength based tasks.

When introducing a new supplement or changing the dose or administration of an existing supplement, it is paramount that the side effects of the supplement are carefully considered, and the health and wellbeing of the individual are always put first. Caffeine has been shown to acutely increase blood pressure [51] post ingestion. This identifies a possible area of concern for those participating in maximal effort weightlifting, due to the increase in blood pressure reported during these tasks [52]. Although uncommon and often minor, other more serious, complications include anxiety, restlessness, insomnia, and tachycardia [53]. Some evidence of gastrointestinal upset has also been documented with effects being greater in low habitual users [54]. Subsequently, it is essential that athletes, coaches and practitioners systematically evaluate the risk-benefit ratio, and make an informed decision before embarking on the use of any supplement, after all, ergogenic aids can only offer small improvements in performance, and should only be utilised in addition to a well-structured exercise program.

Conclusion

In summary, the scientific evidence promoting the use of caffeine as an ergogenic aid for muscular strength and endurance is currently ambiguous and equivocal, particularly for female athletes, of which, there is very limited research. Nevertheless due to the limited side effects, and strong evidence supporting the use of the drug in numerous other exercise modes (e.g. endurance) and in various populations, the implementation of caffeine supplementation for muscular strength and endurance has potential justification. The magnitude of benefit appears to be due to a combination of exercise type and individual characteristics that together may combine to offer a potentially highly ergogenic effect.

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