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Influence of caffeine supplementation on bench press performance – review

MATEUSZ HALZ[1], MAGDALENA KASZUBA[1], DAWID GAWEL[1], JAKUB JAROSZ[1], PATRYK MATYKIEWICZ[1], MARTA BICHOWSKA[2]

Abstract

Introduction. **Caffeine (CAF) is widely consumed psychoactive substance and one of the most used supplements. Due to the fact that strength and power training has become an essential component of conditioning programs in most of the competitive sports, the need for more specific analysis of CAF in terms of resistance training has been established. Furthermore, most of the research focused on the acute effects of CAF supplementation on muscle performance utilized the bench press (BP) exercise. Taking into consideration the popularity of the BP exercise, the main purpose of this review is to evaluate the current state of knowledge on the impact of CAF supplementation on the BP performance and to point out practical guidelines.** Material and Methods. **PubMed, Medline and GoogleScholar databases were searched from 2006 to 2020 for studies evaluating the effects of CAF on: (1) maximal muscle strength; (2) power output; and (3) strength-endurance performance as assessed in the BP exercise. Twenty-three articles met the inclusion criteria and were consequently included in the review.** Results. **In general, CAF in doses of 3 to 6 mg/kg has been found to be a safe ergogenic aid during the BP exercise in terms of improving maximal strength and power output, however the impact of CAF intake on strength-endurance is less clear. Additionally, doses of 9 mg/kg and 11 mg/kg might be ergogenic in the improvement of maximal strength and power output, however higher frequency of side effects observed has to be considered in supplementation strategy.** Conclusions. **The performed review showed that acute CAF intake can be an effective strategy to improve resistance training outcomes for maximal strength and power output tests during the BP exercise. However, extrapolation of these guidelines to long--term benefits of CAF influence on the BP exercise remains limited due to lack of evidence in this area.**

KEYWORDS: strength endurance, power output, maximal strength, ergogenic aid, upper-limbs.

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Corresponding author: dawidgawel777@gmail.com

[1] *The Jerzy Kukuczka Academy of Physical Education in Katowice, Institute of Sport Sciences, Katowice, Poland*
[2] *Gdansk University of Physical Education and Sport, Faculty of Tourism and Recreation, Gdansk, Poland*

Introduction

Caffeine (CAF) is widely consumed psychoactive substance and one of the most used supplements by competitive athletes [53]. It has been shown not only to improve physical performance tasks, but also cognitive aspects, for instance, alertness, concentration, vigilance, and memory, notably in sleep-deprived subjects [42, 48]. CAF supplementation for improving sports performance has become particularly popular after the World Anti-Doping Agency (WADA) removed it from the list of prohibited substances in 2004 [15] and nowadays it is ubiquitous in all sport disciplines [53]. There are reports claiming that 75-90% of athletes consume CAF before or during training and competition [13]. However, CAF concentrations in samples from athletes representing strength-related disciplines were significantly higher in comparison to athletes from other sports [53] and increased significantly from 2004 to 2015 [1], which underline the need for more specific analysis of the impact of CAF as regards to resistance training.

Strength and power training has become an essential component of conditioning programs in most of the competitive sports. Thus, optimization of resistance training and the pattern of adaptive changes related to the development of muscular strength and power are the focus of interest of scientists and coaches [12], who are interested in the improvement of maximum strength, as well as the beneficial changes in power output and strength-endurance. Muscular strength is defined as “the capability to exert force under a particular set of biomechanical conditions” [10] and has been recognized as a vital factor impacting performance in various sports [65]. Muscular strength development is most often accomplished by means of resistance training [33] and commonly measured by the 1RM test [58]. The 1RM test is considered the gold standard for assessing muscle strength under non-laboratory conditions and should be conducted over a specific range of motion and with use of a proper technique [34, 60]. Similarly, to muscular strength, the muscular power is acknowledged to be a crucial component as regards to athletic performance in many sport disciplines and is likewise developed by means of resistance training [62]. Muscular power is defined by “the ability to exert a maximal force in as short a time as possible, as in accelerating, jumping and throwing implements”. It is dependent on optimal values of the force generated by the muscles and the velocity of the movement, thus it is usually described by the relationship between the two aforementioned components [62].

Interestingly, there is a growing number of studies analyzing the effects of CAF supplementation on various aspects of resistance training. Furthermore, most of the research focused on the acute effect of CAF supplementation on muscle performance utilized the bench press (BP) exercise. The BP exercise is a commonly known resistance exercise, primarily used for the upper-body strength and power development among both recreational and professional athletes [36, 57, 68]. The BP exercise is performed as one of the specific disciplines in powerlifting [61]. It is also used by athletes in most strength-speed oriented sport disciplines [52]. The pectoralis major, anterior deltoid and triceps brachii are the main muscles involved in the BP exercise [31, 32], however it should be noted that various factors such as grip width [57], variation of the exercise [36, 59] or the type of the bar [31, 36] can affect exercise performance during the BP.

It is commonly known that supplementation, which could directly impact acute and chronic performance responses play an important role in improving the effectiveness of resistance training [9, 35, 67]. Interestingly, from investigating CAF’s impact on aerobic exercise, recently the research interest has focused on anaerobic exercise performance outcomes, such as maximal strength, strength-endurance, and muscle power [26]. It should be emphasized that all of above-mentioned performance indicators of resistance training could be measured during the BP exercise, which is widely used in experimental protocols. Taking into consideration the popularity of the BP exercise [59] the main purpose of this review is to evaluate the current state of knowledge of CAF supplementation on the BP performance and to point out the practical guidelines of CAF supplementation when performing the BP exercise. The authors believe that the results will benefit athletes and practitioners in various sports in which muscle strength and/or power of upper limbs are important determinants of performance.

Mechanisms of action of caffeine during bench press performance

The mechanisms responsible for the ergogenic effect of CAF are related to the effect on various tissues, organs and systems of the human body. The potential effects of CAF at the cellular level can be explained by three possible mechanisms of action: a) the antagonism of adenosine receptors, especially in the central nervous system (CNS); b) the mobilization of intracellular calcium storage; c) the inhibition of phosphodiesterase. However, the influence of CAF on resistance performance is mostly associated with the impact of CAF on the CNS and antagonistic effects on adenosine receptors. Due to the fact that CAF is structurally similar to adenosine, its consumption blocks the binding of adenosine with A1 and A2A receptors and supports the release of neurotransmitters such as noradrenaline, dopamine, acetylcholine and serotonin [51], which affects the central nervous system and alters arousal and leads to improved performance. Moreover, through its action on adenosine receptors which are involved in nociception, CAF plays an important role in pain modulation [6]. It is important because resistance exercise may provide significant increases in pain perception [11]. Thus, it is possible that the improvement in performance during resistance exercise may be associated with better pain management. In addition, CAF may also increase the release of calcium from the sarcoplasmic reticulum as well as the recruitment of motor units, which may impact muscle contraction strength and help explain some of the ergogenic effects of CAF on resistance exercise performance [51]. Moreover, studies by Tallis et al. [50] and Mohr et al. [39] suggest that CAF may have a direct effect on skeletal muscle tissue, which could also explain its ergogenic effects. Lastly, factors such as motivation and belief due to CAF consumption may influence the response after CAF intake [48]. However, the placebo effect of CAF was examined only in a few studies analyzing the resistance exercises [19, 48], which found conflicting results. Nonetheless, currently psychological factors associated with CAF are often unaddressed in most experimental designs.

Caffeine dose and timing

Current studies confirmed the ergogenic effect of acute CAF intake in resistance training at doses of 3 to 6 mg/kg [29, 30]. However, the administration of a low CAF dose (~3 mg/kg bm) is mostly associated with action through the CNS and do not provide changes in exercise heart rate and the levels of catecholamines, lactate, free fatty acids, and glycerol [49]. Moreover, it has been shown that the plasma CAF levels needed to induce changes in the metabolic tissues are significantly higher than required to impact the adenosine receptors in the brain and peripheral nervous system [21]. Given the fact, that improving resistance performance may be related to several mechanisms of action, it might be concluded that there could not be major ergogenic effects with CAF doses of ~3 mg/kg bm or less where plasma levels are 15-20 μmol/L. Interestingly, for the resistance training the most typically used doses represents a range of 3 to 6 mg/kg, but two studies have shown a positive effect of higher doses varying from 9 to 11 mg/kg [41, 55]. It has been suggested that the CAF dose used could depend on the magnitude of load used, and higher CAF doses may be necessary when high loads are utilized, despite the appearance of side effects [41, 64]. Hence, the optimal dose may differ depending on the type and duration of the exercise, the type of contraction, and previous habituation to CAF [26, 30, 41, 47]. The recommended time of consumption is 30 to 90 minutes before exercise, while the form of supplementation (capsules, liquid, powder) of CAF is less important due to similarly quick absorption after acute intake [26].

Habitual intake, side effects and inter-individual differences in caffeine ergogenicity

It should be noted, that the daily level of CAF consumption and habituation to this supplement may modify the ergogenic effect of CAF on resistance performance. It could be important for the growing number of athletes, who typically consumed CAF on a regular basis [1]. According to Fredholm et al. [21], regular consumption of CAF is associated with an increase in adenosine receptors, which may have an impact on the effectiveness of CAF's blocking effect. Moreover, the production of cytochrome P450 enzymes responsible for CAF metabolism is also upregulated by regular CAF consumption, as a result increasing CAF metabolization speed in habitual users [43]. Repeated exposure to CAF also blunts some of the physiological responses observed by CAF-naïve individuals following acute CAF administration, such as increased adrenaline secretion [5]. In fact, several studies analyzing the effectiveness of CAF ingestion in resistance exercises conducted on habituated participants showed only partial improvement of performance [55] or did not observe a positive effect of CAF supplementation [56, 64]. However, several studies have shown that habitual consumption of CAF did not worsen the ergogenic benefits of acute supplementation [24, 27]. Pickering and Kiely [43] suggested that the maintenance of the ergogenic effect of CAF does still occur in habituated subjects but the used dose has to be higher than the typical daily level of CAF intake. However, due to several inconsistencies including various methods of classification, level of habitual intake and methods of its evaluation, which was recently discussed by Filip et al. [18], this issue is still unsolved and requires further research.

Although higher doses of CAF may seem beneficial for habituated users [43], it should be noted, that various side effects of CAF consumption have been shown to occur, including anxiety, nervousness, increased urine output, insomnia, tachycardia and heart palpitations [43, 64]. Generally CAF doses between 9 and 13 mg/kg seem to elicit severe side effects [64], as well they tend to be the most pronounced in individuals non-habituated to CAF [43]. Wilk et al. [64] have shown that high CAF doses (9 and 11 mg/kg) also cause negative side effects in habituated individuals, furthermore, these adverse effects can persist even 24 hours after ingestion impacting sleep and activities to be performed on the following day. It is important to note, that among habituated CAF users withdrawal is also often associated with negative effects, such as nausea, headaches, irritability and muscle pain [43]. Another factor to be considered as regards to CAF consumptions is the fact, that there are different individual responses following CAF ingestion, which may be influenced by variation in individual genotype (variation within CYP1A2 and ADORA2A genes), environmental factors or epigenetic mechanisms [43]. A single nucleotide polymorphisms within aforementioned genes has been shown to affect the speed of CAF metabolisation (CYP1A2) as well as habitual caffeine use and sleep disturbances (ADORA2A). Thus, substantial differences in performance improvement between individuals following CAF ingestion have been shown to occur, ranging from highly ergogenic to ergolytic [42, 43].

Gender is also a significant factor as regards to CAF ergogenicity [42, 56]. Although CAF has been shown to be ergogenic for both male and female subjects, due to the use of oral contraceptives as well as differences in menstrual cycle stage, CAF metabolization speeds may be altered among women [42]. It has been suggested that a longer time between CAF ingestion and exercise may be beneficial for females [42].

Effects of caffeine on maximal strength

With currently available scientific studies, it is difficult to confirm the positive effect of CAF on maximal strength during the BP exercise. For instance, several studies found no effect of CAF on the 1RM test during the BP exercise [4, 28, 64, 69], but contrary different investigations showed the positive effect of CAF supplementation on maximal strength [2, 7, 16, 23, 46]. The inconsistencies in results of the studies can be explained mainly by differences in characteristics of participants including a) training experience, b) strength level c) relation of used CAF dose to the level of habitual CAF intake. It is worth noticing, that studies, which involved participants who reported lower experience in resistance training [2, 23] showed a positive effect of CAF supplementation. Investigations including athletes with high training experience [4, 28, 69] did not confirmed the ergogenic effect of CAF. Additionally, in research which did not observe a significant increase in maximal strength [4, 28, 69], the initial 1RM in the BP exercise was higher than 100 kg, corresponding to at least 120% of the participants body mass. Pickering and Grgic [42] suggested that ergogenicity of CAF can be also connected to the sports level. For highly trained athletes there is less ‘potential for improvement’ after CAF ingestion because they are towards the upper end of their individual performance capabilities and are approaching absolute physical limits [8]. However, in these few studies, the positive trend after CAF intake was observed, which suggests the ergogenic effect but of a lower magnitude. Unfortunately, in most of the research analyzing the impact of CAF on maximal level of strength during the BP exercise inclusion criteria did not include the strength level of participants and did not estimate relationship between 1RM to body mass ratio, which makes it difficult to reach the final conclusion, if the ergogenic effect depends on the level of maximal strength. Thus, future studies need to analyze effectiveness of CAF ingestion on maximal strength in homogenous group of CAF intake.

The effectiveness of acute CAF intake on maximal strength could also be connected with used CAF dose and/or its relation to the level of daily CAF consumption. In fact, in the study by Wilk et al. [63], resistance-trained individuals (1RM in BP with a load of at least 120% of body mass; 118.3 ± 14.5 kg; mean ± standard deviation) improved the 1RM in BP exercise after intake 9 and 11 mg/kg of CAF, despite observed relative high frequency of side effects. Pallarés et al. [41] suggested that for higher loads, typically used CAF doses may not be sufficient in order to provide an ergogenic effect. Taking into consideration that most of previous studies used 6 mg/kg of CAF (Table 1), future studies need to analyze effectiveness of higher doses, especially in individuals habituated to CAF.

Unfortunately, only two studies investigating CAF impact on BP performance enrolled female subjects [23, 46] and interestingly showed a positive effect of CAF supplementation. However, those studies were conducted on participants with a relatively low level of 1RM, corresponding to approximately 50% [46] and 80% [23] of their body mass. Thus, further research is necessary in order to establish the ergogenic effect of CAF on maximal strength in female athletes, especially those on the elite level. Additionally, a limitation of this studies is that hormonal changes, as a result of the menstrual cycle were not controlled. To date, it remains unclear whether or not the ergogenic effect of CAF supplementation in terms of resistance training depends on the phase of menstrual cycle, thus this issue should be taken into consideration in future studies.

Effects of caffeine on power output

To date, several researches have analyzed the effects of CAF on power output during typically used dynamic BP exercises (Table 2). Interestingly, most of conducted studies showed the positive effect of CAF on power output and movement velocity during the BP exercise [20, 22, 37, 40, 41, 55]. However, in all of performed studies performance was assessed by using tools that measure bar velocity (such as linear position transducers). This might suggest that CAF has a more pronounced effect on muscle contraction velocity rather than on maximal force production during the BP exercise. Moreover, recently performed meta-analysis confirmed that CAF is highly ergogenic as regards to movement velocity during resistance exercise [45], which is also observed for the BP exercise (Table 2). It should be noted, that the effects of CAF might not be uniform

Table 1. Summary of studies exploring the impact of CAF supplementation on maximal strength

Author	Participants gender	Participants age (years)	Training experience	Daily CAF intake (mg/day)	Dose of CAF used (mg/kg)	CAF form	Timing of CAF ingestion before the experimental session (minutes)	Main findings
Arazi et al. [2]	men (15 participants)	21.16 ± 3.9	6-12 months 1RM = 56.30 ± 6.49 kg	no data	6	capsule	60	↑ 1RM; ↑ 3.42 ± 7.28 kg
Astorino et al. [4]	men (22 participants)	23.4 ± 3.6	6.0 ± 2.8 years 1RM = 114.9 ± 22.8 kg	110.5 ± 152.3	6	capsule	60	↔ 1RM
Beck et al. [7]	men (37 participants)	21 ± 2	1 year (at least) with 3-4 training sessions per week 1RM = 74.8 ± 12.5 kg	no data	~ 2.4 (201 mg total)	capsule	60	↑ 1RM; ↑ 2.1 kg
Diaz-Lara et al. [16]	men (14 participants)	29.2 ± 3.3	elite athletes; 5 years (at least) 1RM = 90.5 ± 7.7 kg	<60	3	capsule	60	↑ 1RM; ↑ 2.8 kg
Goldstein et al. [23]	women (15 participants)	24.6 ± 6.9	6 months (at least) 1RM = 52.1 ± 11.7 kg	0-416	6	powder	60	↑ 1RM; ↑ 0.8 ± 11.1 kg
Grgic and Mikulic [28]	men (17 participants)	26 ± 6	7 ± 3 years 1RM = 106.9 ± 11.9 kg	58 ± 92	6	liquid	60	↔ 1RM
Sabblah et al. [46]	men (10 participants) and women (8 participants)	24.4 ± 3.2 (men) 27.9 ± 6.13 (women)	moderately active (trained at least 3-5 h per week) 1RM (men) = = 101.5 ± 28.9 kg 1RM (women) = = 32.2 ± 9.0 kg	no data	5	liquid	60	↑ 1RM; ↑ 6.0 kg for men and 3.1 kg for women
Wilk et al. [63]	men (16 participants)	24.2 ± 4.2	4.1 ± 1.4 years 1RM = 118.3 ± 14.5 kg	411 ± 136	9 and 11	capsule	60	↑ 1RM; ↑ 4.0 ± 15.3 kg after 9 mg/kg of CAF and 5.9 ± 11.4 kg after 11 mg/kg of CAF
Williams et. al. [69]	men (9 participants)	26.2 ± 4.3	4.8 ± 2.4 years 1RM = 108.9 ± 6.5 kg	45 ± 20	~ 4 (300 mg total)	capsule	45	↔ 1RM

Note: CAF – caffeine, 1RM – one-repetition maximum

Table 2. Summary of studies exploring the impact of CAF supplementation on power output

Author	Participants gender	Participants age (years)	Training experience	Daily CAF intake (mg/day)	Dose of CAF used (mg/kg)	CAF form	Timing of CAF ingestion before the experimental session (minutes)	Testing protocol	Main findings
Del Coso et al. [14]	3 women and 9 men (12 participants)	30 ± 7	recreationally trained 1RM = 46.3 ± 13.9 kg	<60	1 and 3	energy drink	60	10 sets (1 repetition on a load from 10% to 100% 1RM with 10% increments); MP, PP	↑ PP and MP after 3 mg/kg of CAF
Filip-Stachnik et al. [20]	men (13 participants)	21.9 ± 1.2	recreationally trained 1RM = 79.2 ± 14.9	115.65 ± ± 42.46	6	capsule	60	5 sets (5 reps at 70% 1RM), 4 min of rest between sets, tempo X/0/X/0; MP, PP, MV, PV	↑ MP, MV ↔ PP, PV
Giráldez-Costas et al. [22]	3 women and 9 men (12 participants)	29 ± 8	experience in training + participation in a 4-week velocity-based training program of the BP exercise 1RM no data	<100 mg	3	capsule	60	4 sets (8 reps at 70% 1RM), 3 min of rest between sets, tempo 1/2/X/1; MV, PV, MP, PP	↑ MV, PV, MF, MP, PP
Lane and Byrd [37]	men (23 participants)	22.9 ± 3.6	recreationally trained 1RM = 89.1 ± 24.5 kg	no data	~ 3.5 (300 mg total)	no data	25	10 sets (3 reps at 80% 1RM), 1 min of rest between sets, tempo X/0/X/0; PP, MP, MNP	↑ PV in CAF trial
Lane et al. [38]	women (23 participants)	22.9 ± 3.6	recreationally trained 1RM = 35.2 ± 9.6 kg	no data	~ 1.7 (150 mg total)	no data	25	10 sets (3 reps at 80% 1RM), 1 min of rest between sets, tempo X/0/X/0; PP, MP, MNP	↔ PP, MP, MNP
Mora-Rodríguez et al. [40]	men (12 participants)	19.7 ± 2.8	7.2 ± 2.4 years 1RM = 1.15 ± 0.08 kg per kg of body mass	no data	3	capsule	60	2 sets (6 reps at 85% 1RM), 5 min of rest between sets, bar displacement (velocity) of 1.00 m/s; bar displacement velocity – MPV at 75% 1RM load and 1 m/s load, power output adaptations	↑ V at 75% 1RM load in AM_{CAF} and PM_{PLAC} groups ↑ MPV at 1 m/s load in PM_{PLAC} group

Pallarés et al. [41]	men (13 participants)	21.9 ± 2.9	7.1 ± 3.5 years 1RM = 121.0 ± 22.7 kg	≤70	3, 6 and 9	capsule	60	4 sets (1 set – 3 trials 25% 1RM, 2 set – 2 trials 50% 1RM, 3 set – 1 trial 75% 1RM, 4 set – 1 trial 90% 1RM), 5 min of rest between sets, tempo 2/0/X/0; MPV, MPP	↑ MPV, MPP (25% and 50% 1RM) in all doses of CAF ↑ MPV, MPP (75% 1RM) after 9 mg/kg of CAF ↑ MPV (90% 1RM) after 9 mg/kg of CAF ↑MPP (90% 1RM) after 6 and 9 mg/kg of CAF
Wilk et al. [55]	men (12 participants)	25.3 ± 1.7	4.4 ± 1.6 years 1RM = 128.6 ± 36.0 kg	443 ± 142	3 and 6	capsule	60	5 sets (2 reps at 30% 1RM), 3 min of rest between sets, tempo X/0/X/0; PP, MP, PV, MV	↑ MP, MV after 3 and 6 mg/kg of CAF ↔ PP, PV for 3 and 6 mg/kg of CAF
Wilk et al. [56]	men (15 participants)	26.8 ± 6.2	4.2 ± 1.23 years 1RM = 122.3 ± 24.5 kg	426 ± 102	3, 6 and 9	capsule	60	3 sets (5 reps at 50% 1RM), tempo 2/0/X/0; PP, MP, PV, MV	↔ PP, MP, PV, MV after all CAF doses in each set
Wise et al. [70]	11 women and 12 men (23 participants)	21.2 + 3.7	6.4 ± 3.7 years	no data	328 mg (total)	Instant Via® coffee	30-90	3 sets (1 repetition at 30% 1RM); FOR, PP, PV, RFD	↑ PP, PV in both groups ↑ RFD in men ↔ FOR in both groups

Note: CAF – caffeine, PLAC – placebo, AM – trial at morning, PM – trial in the afternoon, FOR – peak force, MF – mean force, RFD – rate of force development, MNP – minimum power, MP – mean power, MPP – mean propulsive power, PP – peak power, MPV – mean propulsive velocity, MV – mean velocity, PV – peak velocity, V – velocity, 1RM – one-repetition maximum

Table 3. Summary of studies exploring the impact of CAF supplementation on strength-endurance performance

Author	Participants gender	Participants age (years)	Training experience	Daily CAF intake (mg/day)	Dose of CAF used (mg/kg)	CAF form	Timing of CAF ingestion before the experimental session (minutes)	Testing protocol	Main findings
Astorino et al. [3]	men (14 participants)	23.1 ± 1.1	7.5 ± 1.2 years 1RM = 105.2 ± 5.2 kg	218.2 ± ± 28.1	6	capsule	60	4 sets, 2 min of rest between sets, REP to failure at 70-80% 1RM, TWL (weight × REP)	↔ TWL (kg), REP to failure ↓ REP in each set
Astorino et al. [4]	men (22 participants)	23.4 ± 3.6	6.0 ± 2.8 years 1RM = 114.9 ± 22.8 kg	110.5 ± ± 152.3	6	capsule	60	1 set, REP to failure at 60% 1RM, TWL (weight × REP)	↔ REP at 60% 1RM
Beck et al. [7]	men (37 participants)	21 ± 2	1 year (at least) with 3-4 training sessions per week 1RM = 74.8 ± 12.5 kg	no data	~ 2,4 (201 mg total)	capsule	60	1 set, REP to failure at 80% 1RM TWL (weight × REP)	↔ TWL (kg), no data on REP
Diaz-Lara et al. [16]	men (14 participants)	29.2 ± 3.3	elite athletes; 5 years (at least) 1RM = 90.5 ± 7.7 kg	<60	3	capsule	60	1 set, REP to failure at 45,1 ± 12.9% 1RM, velocity, acceleration, muscle power	↑ REP to failure, MP
Duncan and Oxford [17]	men (13 participants)	22.7 ± 6.0	10.4 ± 2.3 years 1RM no data	169-250	5	liquid	60	1 set, REP to failure at 60% 1RM, TWL (weight × REP)	↑ REP to failure, TWL (kg)
Goldstein et al. [23]	women (15 participants)	24.6 ± 6.9	6 months (at least) 1RM = 52.1 ± 11.7 kg	0-416	6	powder	60	1 set, REP to failure at 60% 1RM	↔ REP at 60% 1RM
Green et al. [25]	men (13 participants) and women (4 participants)	21.0 ± ± 1.5 (men) 2.0 ± 1.5 (women)	≥8 weeks 10RM (men) = = 90.0 ± 41.0 kg 10RM (women) = = 35.0 ± 5.9 kg	no data	6	capsule	60	6 sets, 3 min of rest between sets, 3 warm-up sets (no more than 12 REP) and next 3 sets (successful REP to failure); 100% or near 100% of the estimated 10RM	↔ REP to failure
Grgic and Mikulic [28]	men (17 participants)	26 ± 6	7 ± 3 years 1RM = 106.9 ± 11.9 kg	58 ± 92	6	liquid	60	1 set, REP to failure with 60% 1RM	↔ REP to failure at 60% 1RM

Sabblah et al. [46]	men (10 participants) and women (8 participants)	24.4 ± 3.2 (men) 27.9 ± 6.13 (women)	moderately active (trained at least 3-5 h per week) 1RM (men) = = 101.5 ± 28.9 kg 1RM (women) = = 32.2 ± 9.0 kg	no data	5	liquid	60	1 set, REP to failure at 40% 1RM, TWL: 40% 1RM × REP	↑ TWL in men ↔ TWL in women
Wilk et al. [64]	men (16 participants)	24.2 ± 4.2	4.1 ± 1.4 years 1RM = 118.3 ± 14.5 kg	411 ± 136	9 and 11	capsule	60	1 set, REP to failure at 50% 1RM, REP, TUT_{CON}, PP, MP, PV, MV, tempo 2/0/X/0	↑ PV ↔ TUT_{CON}, PP, MP, MV
Wilk et al. [66]	men (20 participants)	25.7 ± 2.2	2.3 ± 0.63 years 1RM = 102.3 ± 8.5 kg	<200 mg/ week	5	capsule	60	1 set, REP to failure at 70% 1RM, PP, MP, PV, MV, VE_{MEAN}, TUT, REP, tempo X/0/X/0	↑ VE_{MEAN} in CAF group ↓ TUT in CAF group ↔ MP, PP, PV, MV, REP
Williams et al. [69]	men (9 participants)	26.2 ± 4.3	4.8 ± 2.4 years 1RM = 108.9 ± 6.5 kg	45 ± 20	~ 4 (300 mg total)	capsule	45	1 set, REP to failure at 80% 1RM, TWL (weight × REP)	↔ TWL (kg)

Note: CAF – caffeine, MP – mean power, PP – peak concentric power, MV – mean concentric velocity, PV – peak concentric velocity, VE_{MEAN} – mean eccentric velocity, TUT – time under tension, TUT_{CON} – time under tension during concentric contractions, 1RM – one-repetition maximum, REP – repetitions, TWL – total weight lifted across various external loads [41]. CAF dose of 3 mg/kg has been shown to be sufficient in order to increase the bar velocity at low to moderate external loads (25--50% 1RM), however at high external loads (90% 1RM) a higher dose of CAF (9 mg/kg) is necessary in order to achieve improvement in bar velocity [41].

Moreover, the different effect of CAF supplementation was observed depending on the time of day. In the study by Mora-Rodríguez et al. [40] trained men performed three exercise trials: a) a morning training session (10:00 am) after the ingestion of 3 $mg \cdot kg^{-1}$ of CAF; b) a morning training session after ingesting a placebo; and c) an afternoon session (6:00 pm) following the ingestion of a placebo. After the intake of CAF in the morning, bar velocity during the BP exercise significantly increased compared to placebo morning trial levels and reached approximately the level of afternoon trial. Results of this study suggest that CAF intake reverses the morning neuromuscular declines, improving performance to the levels of the afternoon trial, which should be taken into consideration while planning supplementation protocol.

However, it should be emphasized, as regards to resistance training, that an improvement of performance in fatigued state is of utmost importance. Unfortunately, most of the previous research analyzing the impact of CAF on the BP exercise used test procedures consisting only of a single set of an exercise. Evidence from studies, where the experimental protocol consisted of more than one set of the BP exercise [22, 37, 38] suggest that the positive effect of CAF supplementation may be accentuated during a whole resistance training session. However, this issue has to be more explored to be satisfactorily translated into meaningful conclusions for resistance training.

Effects of caffeine on strength-endurance performance

Previously conducted meta-analysis and review [44, 54] showed that CAF, when administered in a dose of 5-6 mg/kg can have an ergogenic effect on strength-endurance during resistance exercise. However, the results of the studies utilizing the BP exercise showed conflicting results. Most of the studies (Table 3) did not show the positive effect of CAF on strength-endurance during the BP exercise [3, 4, 7, 23, 25, 28, 63, 69]. On the contrary, in two investigations conducted by Diaz-Lara et al. [16] and Duncan and Oxford [17] CAF improved the number of repetitions performed to muscular failure. Additionally, in the study of Sabblah et al. [46] there was a tendency towards improvement in total weight lifted during a strength-endurance test performed to muscular failure at 40% of 1RM but only for males, suggesting a sex difference in responses to CAF ingestion.

It should be taken into consideration that differences between studies can be explained by different experimental protocols and methods used to analyze performance. In most of the studies, strength test was a part of protocol, consisting of a battery of performance tests and usually it was assessed in the latter/last part of the testing sequence. Thus, the fatigue state may have impacted obtained outcomes and different results might have been showed if strength-endurance had been measured separately or at the beginning of the testing protocol [28]. Additionally, most of the studies analyzed only the number of repetitions performed to the muscular failure. However, according to Wilk et al. [66] total time under tension (TUT) is a more accurate and credible indicator of work performed compared to the number of performed repetitions (REP). TUT provides accurate information about the duration of resistance effort for a set and for the entire training session and determines how long the resistance effort lasts regardless of the number of REP performed. Interestingly, in the study by Wilk et al. [66] CAF ingestion increased bar velocity in the eccentric phase of the movement, what resulted in shortening of the TUT needed for performing a specific number of repetitions, without decreasing power and velocity in the concentric phase of the movement. In other words, ingestion of CAF did not improve the number of REP performed to failure but reduced TUT. Thus, future studies have to include additional performance measurements, including TUT and bar velocity in order to better explore the impact of CAF on strength-endurance.

Conclusions

In general, CAF in doses of 3 to 6 mg/kg has been found to be a safe ergogenic aid during the BP exercise in terms of improving maximal strength and power output, but the impact of CAF intake on strength endurance is less clear. Additionally, doses of 9 mg/kg and 11 mg/kg might be ergogenic in order to improve maximal strength and power output, however higher frequency of side effects observed have to be considered in supplementation strategy. It is possible that habituation to CAF may modify the ergogenic benefits of CAF on BP performance but future studies need to analyze the effectiveness of CAF in groups with different level of daily consumption. Caution is advised when extrapolating these conclusions in context of improving performance during an entire training session as the vast majority of studies include single repetition or set of the BP exercise. Moreover, most of the research conducted in this area involved only male participants and future studies need to explore if such acute increases in BP performance after CAF ingestion also occurs among women. Finally, long-term studies are needed in order to explore whether or not these acute performance responses also impact long-term adaptations in the BP exercise.

Conflict of interests

The authors declare no conflict of interest.

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