Effects of Caffeine on Resistance Exercise: A Review of Recent Research

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Effects of caffeine on resistance exercise: a review of recent research

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Abstract

In the last few years, a plethora of studies explored the effects of caffeine on resistance exercise, demonstrating that this field of research is growing fast. This review evaluated and summarized the most recent findings. Given that toxic doses of caffeine are needed to increase skeletal muscle contractility, the binding of caffeine to adenosine receptors is likely the primary mechanism for caffeine's ergogenic effects on resistance exercise. There is convincing evidence that caffeine ingestion is ergogenic for: (i) one-repetition maximum, isometric, and isokinetic strength; and (ii) muscular endurance, velocity, and power in different resistance exercises, loads, and set protocols. Furthermore, there is some evidence that caffeine supplementation also may enhance adaptations to resistance training, such as gains in strength and power. Caffeine ingestion is ergogenic for resistance exercise performance in females, and the magnitude of these effects seems to be similar to those observed in men. Habitual caffeine intake and polymorphisms within *CYP1A2* and *ADORA2A* do not seem to modulate caffeine's ergogenic effects on resistance exercise. Consuming lower doses of caffeine (e.g., 2 to 3 mg/kg) appears to be comparably ergogenic as consuming high doses of caffeine (e.g., 6 mg/kg). Minimal effective doses of caffeine seem to be around 1.5 mg/kg. Alternate caffeine sources such as caffeinated chewing gum, gel, and coffee are also ergogenic for resistance exercise performance. With caffeine capsules, the optimal timing of ingestion seems to be 30 to 60 minutes pre-exercise. Caffeinated chewing gums and gels may enhance resistance exercise performance even when consumed 10 minutes before exercise. It appears that caffeine improves performance in resistance exercise primarily due to its physiological effects. Nevertheless, a small portion of the ergogenic effect of caffeine seems to be placebo-driven.

Key points

- There is convincing evidence that caffeine ingestion is ergogenic for one-repetition maximum, isometric, and isokinetic strength, as well as muscular endurance, velocity, and power in different resistance exercises, loads, and set protocols.
- Habitual caffeine intake and polymorphisms within *CYP1A2* and *ADORA2A* do not seem to modulate caffeine's ergogenic effects on resistance exercise.
- Lower doses of caffeine (e.g., 2 to 3 mg/kg) appear to be comparably ergogenic as high doses of caffeine (e.g., 6 mg/kg). Minimal effective doses of caffeine seem to be around 1.5 mg/kg. Caffeine sources such as caffeinated chewing gum, gel, and coffee are also ergogenic for resistance exercise performance.
- With caffeine capsules, the optimal timing of ingestion seems to be 30 to 60 minutes pre-exercise. Caffeinated chewing gums and gels may enhance resistance exercise performance even when consumed 10 minutes before exercise.
- It appears that caffeine improves performance in resistance exercise primarily due to its physiological effects. Nevertheless, a small portion of the ergogenic effect of caffeine seems to be placebo-driven.

1. Introduction

Caffeine is a highly popular ergogenic aid [1, 2]. Studies have evaluated the effects of caffeine on various components of exercise performance, including resistance exercise [3, 4]. In 2018, we published a review that summarized and critically evaluated the effects of caffeine supplementation on different aspects of resistance exercise performance [4]. Since this review, over 50 new studies [5-55] have been published that explored the effects of caffeine on resistance exercise, demonstrating that this field of research is growing fast. These studies provided novel data for: (i) the mechanisms of the ergogenic effects of caffeine on resistance exercise; (ii) the general acute and long-term effects of caffeine on resistance exercise; (iii) the effects of caffeine in women; (iv) the relationship between habitual caffeine intake and the ergogenic effects of caffeine supplementation; (v) the associations between genetic variations and the individual responses to caffeine ingestion; (vi) the optimal protocols of caffeine supplementation (i.e., dose, source, and timing of caffeine); and (vii) the placebo effects of caffeine on resistance exercise. Given that this is a rapidly developing field of research, the aim of this article was to provide an updated overview of the most recent studies exploring caffeine’s effects on resistance exercise. By doing so, it is hoped that this article will guide research areas for future studies on the topic and help optimize caffeine supplementation in practice.

2. Mechanisms for the ergogenic effects of caffeine on resistance exercise

It is generally accepted that caffeine ingestion enhances performance due to its effects on adenosine receptors (i.e., central mechanisms) [56, 57]. Caffeine has a similar molecular structure to adenosine [58]. Therefore, after ingestion, caffeine binds to adenosine receptors and alleviates fatigue sensations, ultimately resulting in improved exercise performance [56].

Still, some data indicate that caffeine may also enhance performance due to its local effects (i.e., effects directly on skeletal muscle) [59]. These ideas have been developed using animal models [60, 61]. In vitro studies that used isolated muscle fibers commonly report that the application of caffeine directly potentiates skeletal muscle force production [60, 61]. The direct effects of caffeine on force production are believed to be due to caffeine's binding on the skeletal muscle ryanodine receptor 1, resulting in increased sarcoplasmic reticulum calcium ion release [33, 62]. However, studies that use isolated muscle fibers commonly apply caffeine doses that would be toxic in humans [33].

A recent study [33] included 21 active men and evaluated the evoked forces of the femoral nerve before and one hour after the ingestion of 6 mg/kg of caffeine or placebo. Additionally, this study explored submaximal tetanic force in mouse flexor digitorum brevis muscle fibers using various caffeine doses. In human participants, caffeine ingestion did not enhance electrically evoked forces. In the mouse flexor digitorum brevis muscle fibers, caffeine increased tetanic force; however, the doses required to elicit such an effect were 15 to 35-fold above physiological concentrations reported in humans. This led the authors to two conclusions: (a) toxic doses of caffeine are needed to increase skeletal muscle contractility; and (b) central effects of caffeine (i.e., binding to adenosine receptors) likely explain caffeine's ergogenic effects [33]. Such conclusions are essentially supported by two studies conducted in humans. In these studies [6, 27], the participants performed resistance exercise tasks to failure (i.e., knee extension or unilateral isometric plantar flexor contractions) after consuming 3 or 6 mg/kg of caffeine. Several neurophysiological parameters were evaluated, and the data indicated that caffeine ingestion improved mean torque and training volume by enhancing neural drive, confirming that caffeine elicits the majority of its effects on the nervous system [6, 27].

3. Acute effects of caffeine on resistance exercise performance

3.1. Muscular strength

In our previous review [3], we concluded that caffeine ingestion likely has an ergogenic effect on one-repetition maximum (1RM) strength and that future research is needed to establish if there is a difference in caffeine's effects on 1RM strength between the upper and lower body. Several recent studies [8, 22, 35, 52-54] evaluated caffeine's effects on 1RM strength. Our research group studied the effects of caffeine on 1RM strength in the bench press and squat [22]. An ergogenic effect of caffeine was found in both exercises, even though the effects were small (Cohen's *d*: 0.07 to 0.15). These findings were essentially confirmed by three other studies [35, 52-54] that also reported an ergogenic effect of caffeine on 1RM strength in the squat (Cohen's *d*: 0.27) and bench press (Cohen's *d*: 0.11 to 0.45). Out of all new studies that explored the effects of caffeine on 1RM strength, only one [8] did not find a significant difference between caffeine and placebo. Still, it should be considered that even in this study, the effects favored caffeine (Cohen's *d*: 0.14 to 0.19), and the lack of significance might be due to the small sample size ($n = 12$). Additionally, this study provided caffeine in an absolute dose of 300 mg, which likely created a variation in responses between participants because the relative doses ranged from 3.3 to 4.5 mg/kg.

All of the recently published studies included resistance-trained participants, which provides the opportunity to compare the effects of caffeine on 1RM strength among trained individuals with previous studies that included untrained participants. When analyzing the data, it seems that the effects of caffeine on 1RM strength are similar among resistance-trained (Cohen's *d*: 0.07 to 0.45) [22, 35, 52-54] and untrained participants (Cohen's *d*: 0.06 to 0.49) [63-65].

However, none of the studies included both trained and untrained participants and directly compared the ergogenic effects of caffeine among these populations, which future studies may consider performing.

Based on the current research, it can be concluded that caffeine supplementation in relative doses enhances upper and lower-body 1RM strength. The ergogenic effect of caffeine on 1RM strength does not seem to depend on training status. However, the effects tend to be small and likely have the greatest practical relevance to athletes competing in strength-based sports, even though they may be of value to other sports where maximum strength is an important muscular quality.

Studies have also provided novel data that expanded our knowledge about caffeine's ergogenic effects on isometric and isokinetic strength [9, 25, 31, 32, 35, 37, 45, 49, 66, 67] (Table 1). These studies have reinforced that caffeine ingestion has a significant ergogenic effect on isometric and isokinetic strength, with effect sizes ranging from 0.15 to 0.65 [9, 25, 32, 35, 49]. Besides affecting maximum strength, caffeine ingestion also has a moderate effect (Cohen's *d*: 0.56) on the rate of torque development [37]. Three studies [31, 37, 45] did not find performance-enhancing caffeine on isometric or isokinetic strength, even though it should be considered that the effects in all of these studies highly favored the caffeine condition (*p*-values ranged from 0.054 to 0.067). In summary, the current data confirm that caffeine ingestion enhances isometric and isokinetic strength. Given that isometric and isokinetic strength assessment is more likely to be used for testing purposes and less likely as a training tool [68], caffeine intake should be standardized or restricted before evaluating isometric or isokinetic strength.

3.2. Muscular endurance

Over 20 new studies explored the effects of caffeine on different muscular endurance outcomes [6, 8, 9, 11, 16, 21, 22, 26, 29, 30, 35, 36, 38, 41, 44, 45, 48, 49, 52, 53, 54, 55]. An ergogenic effect of caffeine on muscular endurance was observed in the majority of these studies, with the effect sizes ranging from small to large (Cohen's *d*: 0.18 to 2.21). When examining the difference in means, the increase in the number of repetitions per set following caffeine ingestion generally ranges from 1 to 4 additional repetitions [21, 22, 30, 35, 36, 38, 41, 44, 45, 48]. The positive effects of caffeine on muscular endurance have been established for single and multiple-set protocols [11, 30, 36, 38, 44]. Additionally, the ergogenic effects of caffeine on muscular endurance do not seem to be load-dependent as they are observed in studies using loads of 30%, 60%, 70%, and 85% of 1RM [21, 35, 38, 44].

One recent meta-analysis [14] explored the effects of caffeine on muscular endurance in the bench press and leg press. For the bench press, this meta-analysis reported that caffeine ingestion enhanced performance by one additional repetition, whereas for the leg press, there was no significant difference between caffeine and placebo [14]. Still, these results should be interpreted with caution, given that the data were analyzed using differences in means instead of the standardized mean difference. This is relevant to mention, given that there was large heterogeneity in the loads used for the muscular endurance test among the included studies. For example, some studies used 30% of 1RM, and others used up to 80% of 1RM [44, 69]. In this context, it should be considered that an improvement of one repetition is much less practically important when performing a set to failure with 30% of 1RM in comparison to performing a set with 80% of 1RM. Additionally, some studies [8, 21, 22, 70] that satisfied the inclusion criteria of this review were not included, highlighting the need for caution when interpreting these data. It should be considered that evaluating only the number of performed repetitions may be considered a crude measure of muscular endurance. Therefore, recent studies have also quantified exercise volume using time under tension (i.e., the sum of time spent in the concentric and eccentric phases) [52]. Using multiple performance variables may be important because one recent study [52] did not find a significant difference between caffeine and placebo for the total number of repetitions; however, caffeine ingestion increased time under tension (Cohen's *d*: 0.61). Overall, current evidence suggests that caffeine ingestion is ergogenic for muscular endurance and that these effects are consistent across different resistance exercises, loads, and set protocols (i.e., single or multiple sets).

Besides assessing the quantity of performed repetitions, researchers have started exploring caffeine's effect on the quality of repetitions. In a study by our research group [21], we had the participants perform a single set to muscular failure in the bench press with 85% of 1RM following the ingestion of caffeine (3 mg/kg) or placebo. During the test, a linear position transducer that measured velocity and power of every repetition was attached to the barbell. Caffeine ingestion enhanced the quantity of performed repetitions as the participants performed one additional repetition following caffeine intake. In addition to the number of repetitions, we explored velocity and power output of repetitions by matching the number of repetitions between the placebo and caffeine conditions. For example, if a participant performed 8 repetitions following caffeine ingestion and 7 following placebo ingestion, the data from the first 7 repetitions were analyzed. We found that caffeine ingestion had a substantial positive effect on the quality of repetitions, as evident by higher mean and peak power and velocity (Cohen's *d*: 0.27 to 0.85).

A similar approach was adopted by another study that used a protocol involving 4 sets of 8 repetitions at 70% of 1RM in the bench press following caffeine and placebo ingestion [17]. Similar to our findings, this study also reported an ergogenic effect of caffeine on velocity and power outcomes (Cohen's *d*: 0.26 to 0.62). This research area is highly relevant from a practical perspective, given that for some training adaptations, the quality of performed repetitions is likely more important than its quantity. This idea is essentially supported by studies that utilize velocity-based training [71, 72]. In one such study [71], training at a 20% velocity loss produced similar gains in squat strength and greater gains in countermovement jump height than training at a 40% velocity loss, despite the 20% velocity loss group performing 40% fewer repetitions.

3.3. Velocity and power

The number of studies exploring the effects of caffeine on velocity and power in resistance exercise has been linearly increasing in recent years [7, 8, 12, 21, 23, 28, 40, 46, 47, 50, 52, 55]. In one of the studies [21] by our research group, we explored caffeine's effects (3 mg/kg) on velocity and power using loads of 25%, 50%, 75%, and 90% of 1RM. Even though it has been previously suggested that very high doses of caffeine (i.e., 9 mg/kg) are needed to enhance velocity and power when using high loads [73], we observed an ergogenic effect of caffeine at all loads. Moreover, the effectiveness of caffeine also seemed to increase with the corresponding increase in the load, given that the effect sizes ranged from 0.20 to 0.29, 0.36 to 0.50, and 0.57 to 0.61 at loads up to 50%, 75%, and 90% of 1RM, respectively. Positive effects of caffeine on velocity and power were also reported in other studies using varying loads (e.g., 30%, 50%, 75%, 80%, and 90% of 1RM) and exercises such as the bench press and squat [12, 46, 47, 50]. A meta-analysis [39] published in 2020 also explored the effects of caffeine on velocity in resistance exercise. This meta-analysis [39] included 12 studies and analyzed the effects of caffeine on mean and peak velocity. Subgroup analyses explored the effects of caffeine on velocity in lower-body vs. upper-body exercises and on velocity when using low-loads (<30% of 1RM), moderate loads (30% to 70% of 1RM), and high-loads (70% to 100% of 1RM). Caffeine ingestion had a significant ergogenic effect on mean and peak velocity across all training loads and upper and lower-body exercises. The effect sizes ranged from moderate to large (Cohen's *d*: 0.41 to 0.82). In a sensitivity analysis, exclusion of the unpublished studies changed the effect of caffeine for peak velocity from significant to non-significant. Still, it should also be mentioned that only three published studies focused on peak velocity, which might have caused issues with statistical power in this analysis. Overall, based on the current research, it seems that caffeine has a considerable ergogenic effect on velocity and power in resistance exercise. In some cases, these effects seem to be higher than the effects observed on muscular strength and muscular endurance [39, 74, 75].

4. Long-term effects of caffeine on resistance exercise

An emerging research area is related to caffeine's long-term effects [18, 76, 77]. Given the overwhelming body of evidence supporting the acute ergogenic effects of caffeine on resistance exercise performance, researchers have started exploring if these acute effects, when applied in each training session, also impact long-term adaptations to exercise. Increases in muscular strength and muscle size tend to favor greater training volumes [78, 79]. As caffeine ingestion pre-exercise enhances muscular endurance (i.e., total training volume), a logical rationale can be made that caffeine ingestion before every exercise session will positively impact these long-term adaptations.

Two studies [18, 76] explored this topic and provided some support for this hypothesis. In one study, the researchers randomized 14 resistance-trained participants to two groups [76]. One group ingested 3 mg/kg of caffeine 60 minutes before exercise, while the other group ingested a placebo. Both groups trained 3 times per week for 6 weeks. Before and after the training intervention, 1RM in the bench press and squat was evaluated. The caffeine group improved 1RM in the bench press by 13 kg and in the squat by 27 kg. These gains were significantly larger than those observed in the placebo group (7 kg in the bench press and 11 kg in the squat). Another study [18] essentially used the same design and included 9 participants in the caffeine group (3 mg/kg of caffeine 60 minutes pre-exercise) and 7 participants in the placebo group. The groups trained for 4 weeks, 3 times per week. Participants performed a 1RM bench press test and a force-velocity test that evaluated mean and peak velocity and power using loads from 10% to 100% 1RM. Gains in 1RM strength were similar between the groups. Still, the group that consumed caffeine seemed to have more consistent gains in the force-velocity test. Possible discrepancies between the studies for 1RM strength might be because of the difference in intervention duration (i.e., 6 vs. 4 weeks; 18 vs. 12 training sessions). Future studies may consider utilizing a longer duration intervention to establish the time course of caffeine's effects on adaptations to resistance exercise, where gains in strength are evaluated periodically (e.g., 12 weeks of training with 1RM testing every 3 to 4 weeks). Overall, while the current research supports the positive effects of long-term caffeine supplementation, future longer-duration studies are still needed.

5. Effects of caffeine on resistance exercise in women

The majority of studies that explored the effects of caffeine on exercise performance included males as study participants [3]. This was highlighted in a commentary that summarized data from 362 primary studies on caffeine and exercise and found that only 13% of participants included in the studies were females [80]. Several studies recognized this limitation and directly explored caffeine’s effects on resistance exercise performance in women [25, 28, 35, 36, 40, 48, 49, 52]. One study [35] included 15 resistance-trained women and reported that caffeine ingestion (4 mg/kg) enhanced 1RM strength and muscular endurance in the bench press and squat. Positive effects of caffeine on muscular strength and endurance were essentially confirmed in six other studies [25, 36, 40, 48, 49, 52].

While it is clear that caffeine ingestion enhances resistance exercise performance in women, it is not yet fully clear if there is a sex-specific response to these ergogenic effects. Several studies directly compared the effects of caffeine on muscular strength and endurance between men and women while reporting similar responses between sexes [9, 25, 81]. For example, one study [81] included 10 elite collegiate male and female athletes. The participants ingested caffeine and performed a maximal voluntary isometric contraction test followed by a submaximal voluntary isometric fatigue protocol. Improvement in strength and muscular endurance was around 5% and 15%, respectively, and did not differ between sexes. Another study [25] also evaluated the effects of caffeine on resistance exercise performance in men and women while reporting an ergogenic effect in both sexes. However, it should be mentioned that men responded more consistently to caffeine (i.e., an ergogenic effect was observed in more outcomes) compared to female participants.

Phases of the menstrual cycle are one methodological aspect that warrants consideration when conducting studies in women [82]. Several studies did not standardize for menstrual cycle and still reported an ergogenic effect of caffeine [25, 49, 52]. Nevertheless, caffeine metabolism may vary according to the menstrual cycle phase, possibly impacting caffeine’s ergogenic effects [82]. Even though a variation in caffeine metabolism has been observed, some have questioned the practical significance of these differences, and follow-up research also suggested that the menstrual cycle does not significantly alter the pharmacokinetics of caffeine [82, 83]. In regards to exercise performance, one study [40] evaluated mean and peak velocity at 20%, 40%, 60%, and 80% of 1RM in the half-squat exercise following caffeine or placebo ingestion in the early follicular, late follicular, and mid-luteal phases of the menstrual cycle. Caffeine enhanced mean velocity at 60% of 1RM in the early follicular and late follicular phases. However, these results were somewhat inconclusive given that caffeine improved performance only at 60% of 1RM. This effect might be because the included participants were triathlon athletes and had limited experience with velocity-based training. Another study [35] performed the testing specifically in the early follicular phase and reported that caffeine ingestion (4 mg/kg) provided an ergogenic effect on most analyzed strength and endurance outcomes.

In summary, recent data show that caffeine ingestion is ergogenic for resistance exercise performance in females. The magnitude of these effects seems to be similar to those observed in men. Caffeine's ergogenic effects do not appear to be moderated by phases of the menstrual cycle, even though this topic requires further research.

6. The relationship between habitual caffeine intake and the ergogenic effects of caffeine

Caffeine's performance-enhancing benefits are likely explained by its adenosine antagonist effect. As established in studies using animal models, long-term ingestion of caffeine is associated with an upregulation of adenosine receptors [58, 84]. Therefore, it has been suggested habitual caffeine intake may reduce the ergogenic effect of acute caffeine ingestion on exercise performance. This idea was popularized by Bell and McLellan [85], who observed that low habitual caffeine users (<50 mg/day) experienced greater ergogenic effects of acute caffeine ingestion on cycling performance than high habitual caffeine users (≥300 mg/day). In our previous review [4], we concluded that these findings should not be generalized to resistance exercise as no available studies were using this type of exercise at that point in time. Since then, several studies have been published that provided insights on this topic. One research group conducted a series of studies to investigate the effects of caffeine on resistance exercise performance in groups of participants with a high habitual caffeine intake [50-54]. These studies included participants classified as very high habitual caffeine users as they ingested from 4.9 to 5.8 mg/kg/day of caffeine [50-54]. Despite the high habitual intake, caffeine supplementation (doses from 3 to 11 mg/kg) was ergogenic for mean velocity, mean and peak power, and 1RM bench press strength [50-54]. These studies provide data that high habitual caffeine users still may experience an improvement in performance following caffeine ingestion. However, a limitation of these studies is that they did not directly compare caffeine’s effects among cohorts with varying daily caffeine intake.

This limitation was addressed in one study published in 2020 that compared the effects of caffeine ingestion (3 mg/kg) between low users (65 ± 46 mg/day) and moderate-to-high habitual caffeine users (235 ± 82 mg/day) [19]. Performance outcomes included velocity and power with different loads and muscular endurance in the bench press. Caffeine ingestion was ergogenic for all performance outcomes, but there were no group × condition interaction effects. Another study classified participants into tertiles as low (20 ± 11 mg/day), moderate (88 ± 33 mg/day), and high (281 ± 167 mg/day) habitual caffeine users [11]. Caffeine was provided in the dose of 6 mg/kg and the resistance exercise protocol involved repetitions to muscular failure in 4 sets of squats. As with previous research, this study also reported general ergogenic effects of caffeine but no group × condition interaction effects.

Overall, it seems that habitual caffeine intake does not negate the benefits of acute caffeine ingestion on resistance exercise. In the studies conducted on this topic, an ergogenic effect was observed when the pre-exercise caffeine dose was higher or lower than the amount of caffeine taken habitually by the participants [11, 19, 50]. Based on these findings, it would seem that the amount of caffeine provided pre-exercise does not need to be higher than the dose of caffeine ingested habitually to observe an ergogenic effect [86]. Still, a limitation of the current body of evidence is that studies use different thresholds for classifying habitual caffeine intake [87]. Therefore, a more uniform approach in this field of research is needed [87].

7. Associations between genetic variation and the individual responses to caffeine ingestion

Given that there is substantial individual variability in responses to caffeine ingestion, researchers have devoted their attention to exploring the possible reasons for this between-individual variation [88, 89]. One of the main focuses of this research is on the impact of common polymorphisms within two genes, *CYP1A2* and *ADORA2A* [88]. Rahimi [70] included 30 resistance-trained participants and examined the effects of caffeine (6 mg/kg) on muscular endurance in 3 sets to failure with 85% 1RM. This study found that caffeine ingestion (6 mg/kg) produced greater ergogenic effects in participants with the AA genotype compared to C allele carriers (AC/CC genotype). We used the same exercise protocol, only a lower dose of caffeine (3 mg/kg), but did not find a significant difference in responses between the AA vs. AC/CC genotype (*n* = 22) [21]. Using a handgrip strength test, Muñoz et al. [31] also did not find a significant difference in responses to caffeine ingestion between genotypes in a group of handball players (*n* = 31). In a large sample size study (*n* = 100), Spineli et al. [45] explored the effects of caffeine on muscular endurance and strength. Even though caffeine ingestion enhanced muscular endurance, there were no significant differences between genotypes. Given that the findings by Rahimi [70] were not replicated by three independent research groups from Australia, Brazil, and Spain, it currently seems that *CYP1A2* genotype variations do not modulate caffeine's ergogenic effects on resistance exercise.

Polymorphisms within the *ADORA2A* gene have also received some scientific attention [90]. A small pilot study from 2015 reported that caffeine ingestion is ergogenic for aerobic endurance in the TT genotype but not the CC/CT genotype, with C allele carriers identified as 'non-responders' to caffeine [90]. We evaluated resistance exercise performance following caffeine ingestion in 20 participants classified as C allele carriers [20]. In this study, caffeine was ergogenic in most analyzed outcomes, refuting the notion that individuals with this genotype are 'non-responders' to caffeine [20]. Still, a limitation of this study was the absence of participants with TT genotype. This limitation was addressed in a study [31] that compared the effects of caffeine on handgrip strength between the TT vs. CC/CT genotype and did not find significant between-group differences. As with *CYP1A2*, it seems that *ADORA2A* genotype variations do not determine the ergogenic effect of caffeine on resistance exercise, but this requires much more research.

8. Optimal protocols of caffeine supplementation

8.1. Caffeine dose

When it comes to caffeine dose, it is commonly suggested that optimal effects are obtained when consuming from 3 to 6 mg/kg [3]. We have performed a dose-response study that examined the effects of consuming 2, 4, or 6 mg/kg of caffeine on muscular endurance and strength in the squat and bench press [22]. All three caffeine doses were comparably ergogenic for lower-body muscular endurance (Cohen's *d*: 0.46 to 0.68). For 1RM strength in the squat, only a caffeine dose of 2 mg/kg was ergogenic. In contrast, doses of 4 and 6 mg/kg were required to enhance upper-body strength, with a significant linear trend for the effectiveness of different doses of caffeine. Still, it should be considered that the effect size of caffeine on strength was small (Cohen's *d*: 0.07 to 0.15). Four other studies compared the effects of consuming 3 or 6 mg/kg of caffeine, and all reported that both doses were ergogenic with no significant differences between them [26, 38, 50, 52]. Another study compared 9 and 11 mg/kg and also reported an ergogenic effect of caffeine, with no differences between the doses [53, 54]. However, such large doses seem unnecessary and are associated with a high incidence of side-effects [73]. When discussing minimal effective doses, a recent study [49] reported that a fixed dose of 100 mg (average of 1.5 mg/kg) was ergogenic for muscular strength. Given the previous report [91] that a dose of 1 mg/kg of caffeine did not improve resistance exercise performance, it seems that the minimal ergogenic dose of caffeine for resistance exercise performance is around 1.5 mg/kg [49]. Overall, consuming lower doses of caffeine appears to be comparably ergogenic as consuming high doses of caffeine, with fewer side-effects.

8.2. Caffeine form

Caffeine is most commonly provided using capsules, and the effectiveness of caffeine on resistance exercise is mostly established with this form. Nevertheless, several studies have evaluated the ergogenic effects of other forms of caffeine (chewing gum, gel, coffee) on resistance exercise [13, 26, 46, 47]. One of our studies [46] evaluated the effects of consuming 300 mg of caffeinated chewing gum 10 minutes before exercise on mean velocity, isokinetic peak torque, and power. We observed that caffeinated gum enhanced peak torque and average power (Cohen's *d*: 0.21 to 0.31) and mean velocity at 50%, 75%, and 90% of 1RM (Cohen's *d*: 0.30 to 0.44). Another study [13] also used 300 mg of caffeine in chewing gum provided 5 minutes before completing a running to exhaustion test. Before and after the running test, maximum voluntary strength was evaluated. Muscular strength declined similarly in the placebo (–18%) and caffeine condition (–14%). While this might lead to a conclusion that caffeine ingestion did not attenuate the decline in strength, such inferences might be misguided given that the consumption of caffeine chewing gum also increased running time from 33 minutes (placebo) to 41 minutes [13]. Therefore, total fatigue was not matched between the conditions, and the main finding of this study was that caffeinated chewing gums improved running performance while having the same neuromuscular impairment as the placebo condition [13].

We have also explored the effect of caffeinated gel consumption on isokinetic torque, power, and mean velocity at 50%, 75%, and 90% of 1RM in the bench press [47]. In this study, 300 mg of caffeine consumed in gels 10 minutes before exercise enhanced isokinetic peak torque and power (Cohen's *d*: 0.21 to 0.37), as well as mean velocity (Cohen's *d*: 0.33 to 0.59). One study [26] also evaluated the effect of coffee ingestion with caffeine doses of 3 and 6 mg/kg on muscular endurance in 3 sets to failure in the bench press and squat. Both doses of caffeine enhanced performance in the first set of squats, supporting previous findings [92]. However, these effects were short-lived as no significant difference was found in the second and third set and in the three sets of the bench press.

Based on the most recent evidence, it seems that caffeinated chewing gums and gels may enhance resistance exercise performance even when consumed 10 minutes before exercise, owing to the faster absorption with these sources of caffeine [93]. There is also some additional evidence supporting coffee's ergogenic effect [26], but further research with all alternate caffeine sources on resistance exercise is still needed.

8.3. Timing of caffeine ingestion

The effects of caffeine timing on resistance exercise performance were explored in one study [25]. In this study, the participants ingested 6 mg/kg of caffeine in capsules either 120 minutes, 60 minutes, or 30 minutes before exercise [25]. Muscular strength was evaluated using the isometric mid-thigh pull and isometric/isokinetic knee extensor testing. Generally, the greatest performance benefits were observed when ingesting caffeine 60 minutes pre-exercise, likely because plasma caffeine concentration was also the highest at this time point. Still, for some isokinetic testing outcomes, an ergogenic effect was observed when using caffeine for 30 minutes pre-exercise. In summary, it seems that when consuming caffeine in capsules, the optimal timing of ingestion is around 30 to 60 minutes pre-exercise. Still, as mentioned previously, when it comes to caffeine gum or gels, a shorter waiting time from consumption to the start of the exercise (i.e., 10 minutes) also seems to produce an ergogenic effect on resistance exercise performance [46, 47].

9. Placebo effects of caffeine on resistance exercise

A recent meta-analysis explored the effects of placebo ingestion compared to a no-placebo control condition (i.e., no substance ingestion) [94]. This analysis reported that placebo ingestion provided a small but significant ergogenic effect (Cohen's *d*: 0.09) [94]. Additional analyses from this review also concluded that around 50% of the performance-enhancing benefits of caffeine are attributed to the placebo effect [94]. However, out of the ten included studies, most focused on measures of aerobic endurance, and none utilized a resistance exercise protocol.

When it comes to resistance exercise, researchers have utilized several different designs to investigate the placebo effect [10, 15, 22, 23, 35, 38, 44]. For example, two studies utilized a design that includes a control condition and a placebo condition for which the participants were informed that they ingested caffeine [10, 15]. In one study [15], placebo ingestion—alongside the suggestion that it is caffeine—did not enhance 1RM strength, muscular endurance, or mean power. In another study with the same design [10], placebo ingestion enhanced mean velocity at 50% of 1RM, but not at 60%, 70%, or 80% of 1RM. While this study provided some support for the placebo effect, it remains unclear why such an effect was only observed at 50% of 1RM. However, a limitation of these studies is that they do not include a condition during which caffeine is actually ingested, and performance is directly compared to placebo and control.

Two studies [22, 23] from our group explored the effects of caffeine on muscular strength, endurance, and mean velocity while incorporating a placebo and a control condition. In both of these studies, caffeine ingestion enhanced performance compared to both placebo and control. Additionally, there was no significant difference between placebo and control, as performance values in these two conditions were nearly identical. Polito et al. [38] designed a study where the participants performed 3 sets of different resistance exercises to failure in a control condition and after ingesting 3 mg/kg or 6 mg/kg of caffeine. Even though the participants ingested caffeine on two occasions, they were informed that one of the caffeine doses would be a placebo. Despite providing this information, muscular endurance was comparably enhanced with both caffeine doses. Out of the 14 included participants, 8 and 6 participants believed that caffeine was provided in the 3 mg/kg and 6 mg/kg trials, respectively. However, there were no significant differences between the sessions in which the participants believed that they ingested caffeine compared to those in which they believed that placebo was ingested (even though caffeine was ingested on both occasions).

Finally, it should be mentioned that two studies used a double-blind design and evaluated the effectiveness of the blinding while further comparing the effects of caffeine between those that correctly identified caffeine vs. those that did not correctly identify caffeine [35, 44]. In one study, there was no significant difference in the ergogenic effects of caffeine between these two groups [35]. Another study reported that both 'identifiers' and 'non-identifiers' of the caffeine condition improved muscular endurance following caffeine ingestion, but that the effect was greater among those that correctly identified caffeine (13 vs. 7 repetitions more in 3 sets to failure with 30% of 1RM) [44].

Overall, it seems that caffeine ingestion enhances performance in resistance exercise primarily due to its physiological effects. Nevertheless, a small portion of the ergogenic effect of caffeine appears to be placebo-driven.

10. Conclusions

In the last few years, a plethora of new studies explored the effects of caffeine on resistance exercise, demonstrating that this field of research is growing fast. This review evaluated and summarized the most recent findings. Given that toxic doses of caffeine are needed to increase skeletal muscle contractility, the binding of caffeine to adenosine receptors is likely the primary physiological mechanism for caffeine's ergogenic effects. There is convincing evidence that caffeine ingestion is ergogenic for: (i) one-repetition maximum, isometric, and isokinetic strength; and (ii) muscular endurance, velocity, and power in different resistance exercises, loads, and set protocols. In some cases, the effects of caffeine on velocity and power are higher than the effects observed on muscular strength and muscular endurance. Caffeine supplementation also may enhance adaptations to resistance training. Caffeine ingestion is ergogenic for resistance exercise performance in females, and the magnitude of these effects seems to be similar to those observed in men. Habitual caffeine intake and polymorphisms within *CYP1A2* and *ADORA2A* do not seem to modulate caffeine's ergogenic effects on resistance exercise. Consuming lower doses of caffeine (e.g., 2 to 3 mg/kg) appears to be comparably ergogenic as consuming high doses of caffeine (e.g., 6 mg/kg). Minimal effective doses of caffeine seem to be around 1.5 mg/kg. Alternate caffeine sources such as caffeinated chewing gum, gel, and coffee are also ergogenic for resistance exercise. When consuming caffeine capsules, optimal timing seems to be 30 to 60 minutes pre-exercise. Caffeinated chewing gums and gels may enhance resistance exercise performance even when consumed 10 minutes before exercise. It seems that caffeine enhances performance in resistance exercise primarily due to its physiological effects. Nevertheless, a small portion of the ergogenic effect of caffeine appears to be placebo-driven.

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Jozo Grgic declares he has no conflicts of interest relevant to the content of this article.

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Table 1. Summary of the most recent studies exploring the effects of caffeine on resistance exercise

Reference	**Participants**	**Exercise[a]**	**Outcomes**	**Caffeine supplementation**	**Main findings**
Blake et al. [5]	12 resistance-trained men (at least 6 months of resistance training experience)	Elbow flexion and extension	Total work at 40% of MVIC	350 mg in liquid form ingested 30-minutes pre-exercise	Total work: ↔ between conditions
Bowtell et al. [6]	9 recreationally-active men	Knee extension	Exercise volume	6 mg/kg in capsules ingested 60-minutes pre-exercise	Exercise volume: ↑ following caffeine ingestion (ES: 2.21)
Castillo et al. [7]	20 active men (at least 1 year of resistance training experience)	Flywheel half-squat	Mean and peak power	6 mg/kg in liquid form ingested 45-minutes pre-exercise	Mean power: ↑ following caffeine ingestion (ES: 0.85–1.07) Peak power: ↑ following caffeine ingestion (ES: 1.03–1.40)
Cesareo et al. [8]	12 resistance-trained men (at least 1 year of resistance training experience)	Bench press (1RM: 116 ± 17 kg) and squat (1RM: 141 ± 17)	1RM, number of repetitions at 70% of 1RM, peak and mean power, and peak and mean velocity	300 mg in capsules ingested 90-minutes pre-exercise	↔ between conditions in any of the analyzed outcomes
Chen et al. [9]	10 male and 10 female elite college athletes (sports: tennis, basketball, football)	Knee extension	MVIC and time to maintain 50% of MVIC	6 mg/kg in capsules ingested 24 and 48 hours after EIMD	MVIC: ↑ following caffeine ingestion (ES: 0.34–0.48) Time to maintain 50% of MVC: ↔ between conditions
Costa et al. [10]	4 male Paralympic weightlifting athletes	Bench press (1RM: 69 ± 19 kg)	Peak and mean velocity at 50%, 60%, 70% and 80% of 1RM	Placebo ingestion alongside the suggestion that it is 6 mg/kg of caffeine	Mean velocity at 50% of 1RM: ↑ following perceived caffeine ingestion (ES: 0.36–0.46) ↔ between conditions in any of other analyzed outcomes

De Salles Painelli et al. [11]	36 resistance-trained men (low, moderate, or high habitual caffeine users, *n* = 12 for each group; at least 1 year of resistance training experience)	Leg press (1RM: 365–382 ± 103–117 kg)	Number of repetitions in 4 sets at 70% of 1RM	6 mg/kg in capsules ingested 60-minutes pre-exercise	Number of repetitions: ↑ following caffeine ingestion; ↔ between groups
Degrange et al. [12]	12 resistance-trained men (resistance training 2-3 times per week)	Bench press (1RM: 92 ± 25 kg) and squat (1RM: 121 ± 25 kg)	Mean velocity and power at 80% of 1RM	6 mg/kg in capsules ingested 60-minutes pre-exercise	Mean velocity: ↑ following caffeine ingestion (ES: 1.04–1.06) Mean power: ↑ following caffeine ingestion (ES: 0.24–0.71)
Dittrich et al. [13]	12 trained male runners	Knee extension	MVIC after a running test	300 mg in caffeinated chewing gum consumed 5-minutes before a running test	MVIC: ↔ between conditions
Filip-Stachnik et al. [15]	13 resistance-trained women	Bench press (1RM: 40 ± 10 kg)	1RM, number of repetitions, time under tension, mean and peak power, and mean and peak velocity	Placebo ingestion alongside the suggestion that it is 6 mg/kg of caffeine	↔ between conditions in any of the analyzed outcomes
Filip-Stachnik et al. [52]	21 resistance-trained females (at least 2 years of resistance training experience)	Bench press (1RM: 40 ± 9 kg)	1RM, number of repetitions at 50% of 1RM, time under tension, peak and mean power and peak and mean velocity	3 or 6 mg/kg in capsules ingested 60-minutes pre-exercise	1RM: ↑ following caffeine ingestion (both doses) (ES: 0.11–0.28) Time under tension: ↑ following caffeine ingestion (only 6 mg/kg) (ES: 0.61) ↔ between conditions in any other outcomes

Franco-Alvarenga et al. [16]	12 recreationally-trained cyclists	Knee extension	Time to maintain 70% of MVIC	5 mg/kg in capsules ingested 45-minutes pre-exercise	Time to maintain 70% of MVIC: ↑ following caffeine ingestion (ES: 1.24)
Giráldez-Costas et al. [17]	9 male and 3 female resistance-trained participants (previous resistance training experience)	Bench press	Peak and mean velocity, power, and force, total work, time to peak velocity, power, and force, and time under tension during 4 sets of 8 repetitions at 70% of 1RM	3 mg/kg in capsules ingested 60-minutes pre-exercise	Mean velocity: ↑ following caffeine ingestion (ES: 0.62) Peak velocity: ↑ following caffeine ingestion (ES: 0.44) Mean force: ↑ following caffeine ingestion (ES: 0.04) Peak force: ↔ between conditions Mean power: ↑ following caffeine ingestion (ES: 0.26) Peak power: ↑ following caffeine ingestion (ES: 0.23) Work: ↑ following caffeine ingestion (ES: 0.21) Time to peak velocity: ↓ following caffeine ingestion (ES: 0.18) Time to peak force: ↔ between conditions Time to peak power: ↓ following caffeine ingestion (ES: 0.25) Time under tension: ↓ following caffeine ingestion (ES: 0.23)
Grgic & Mikulic [19]	24 resistance-trained men (*n* = 13 low users and *n* = 11 moderate-to-high habitual caffeine users; at least 6 months of resistance training experience)	Bench press (1RM: 88 ± 21 kg)	Peak and mean velocity and peak and mean power at 25%, 50%, 75%, 85%, and 90% of 1RM, and number of repetitions at 85% of 1RM	3 mg/kg in capsules ingested 60-minutes pre-exercise	↑ following caffeine ingestion in all outcomes (ES: 0.20–0.97); ↔ between groups

Grgic et al. [20]	20 resistance-trained men (all CC/CT genotype; at least 6 months of resistance training experience)	Bench press (1RM: 89 ± 22 kg)	Peak and mean velocity and peak and mean power at 25%, 50%, 75%, 85%, and 90% of 1RM, and number of repetitions at 85% of 1RM	3 mg/kg in capsules ingested 60-minutes pre-exercise	↑ following caffeine ingestion in all outcomes (ES: 0.20–0.97)
Grgic et al. [21]	22 resistance-trained men (*n* = 13 AA genotype and *n* = 9 AC/CC genotype; at least 6 months of resistance training experience)	Bench press (1RM: 89 ± 21 kg)	Peak and mean velocity and peak and mean power at 25%, 50%, 75%, 85%, and 90% of 1RM, and number of repetitions at 85% of 1RM	3 mg/kg in capsules ingested 60-minutes pre-exercise	↑ following caffeine ingestion in all outcomes (ES: 0.20–0.85); ↔ between groups
Grgic et al. [22]	28 resistance-trained men (at least 1 year of resistance training experience)	Bench press (1RM: 106 ± 22 kg) and squat (1RM: 129 ± 24 kg)	1RM and number of repetitions at 60% of 1RM	2, 4, or 6 mg/kg in capsules ingested 60-minutes pre-exercise	1RM squat: ↑ following 2 mg/kg of caffeine ingestion (ES: 0.13–0.15) 1RM bench press: ↑ following 4 and 6 mg/kg of caffeine ingestion (ES: 0.07–0.09) Number of repetitions (squat): ↑ following caffeine ingestion in all doses (ES: 0.46–0.68) Number of repetitions (bench press): ↔ between conditions
Grgic et al. [23]	26 resistance-trained men (at least 1 year of resistance training experience)	Bench press (1RM: 104 ± 16 kg)	Mean velocity at 50%, 75%, and 90% of 1RM	6 mg/kg in capsules ingested 60-minutes pre-exercise	Mean velocity: ↑ following caffeine ingestion at all loads (ES: 0.29–0.46)

Harty et al. [25]	18 resistance-trained men and 11 resistance-trained women (at least 6 months of resistance training experience)	Mid-thigh pull and knee extension	Peak and mean mid-thigh pull force, isometric and isokinetic peak and mean torque, and isokinetic total work	6 mg/kg in liquid ingested 30-minutes, 60-minutes, or 120-minutes pre-exercise	Isometric peak torque: ↑ following caffeine ingestion 30 or 60-minutes pre-exercise (ES: 0.26–0.31) Isometric mean torque: ↑ following caffeine ingestion 30 or 60-minutes pre-exercise (ES: 0.30–0.35) Isokinetic peak torque: ↑ following caffeine ingestion 30-minutes pre-exercise (ES: 0.17) Isokinetic mean torque: ↑ following caffeine ingestion 30-minutes pre-exercise (ES: 0.15) Isokinetic work: ↔ between conditions Peak and mean mid-thigh pull force: ↔ between conditions
Karayigit et al. [26]	17 female team-sport athletes (at least 3 years of resistance training experience)	Bench press (1RM: 64 ± 7 kg) and squat (1RM: 91 ± 7 kg)	Number of repetitions in 3 sets at 40% of 1RM	3 or 6 mg/kg in coffee consumed 60-minutes pre-exercise	Number of repetitions: ↑ following caffeine ingestion (both doses) in the first set (ES: 0.43–0.49); ↔ between conditions in any other outcomes
Kirk et al. [27]	16 resistance-trained men (at least 1 year of resistance training experience)	Plantar flexor contractions	Mean torque during 6 sets at 85% of MVIC	3 mg/kg in capsules ingested 60-minutes pre-exercise	Mean torque: ↑ following caffeine ingestion (ES: 0.24)
Lane & Byrd [24]	23 recreationally-trained men	Bench press (1RM: 89 ± 25)	Peak and mean velocity during 10 sets of 3 repetitions at 80% of 1RM	300 mg in liquid form ingested 20-minutes pre-exercise	Peak velocity: ↑ following caffeine ingestion (ES: 0.88) Mean velocity: ↑ following caffeine ingestion (ES: 0.86)
Lane et al. [28]	23 recreationally-trained females (previous	Bench press (1RM: 35 ± 10 kg)	Peak and mean velocity during 10 sets of 3	150 mg in liquid form ingested 20-minutes pre-exercise	Peak and mean velocity: ↔ between conditions

	experience with the bench press)		repetitions at 80% of 1RM		
Lattari et al. [29]	15 recreationally-trained men (at least 6 months of resistance training experience)	Bench press	Volume load at 10RM	5 mg/kg in capsules ingested 60-minutes pre-exercise	Volume load: ↑ following caffeine ingestion (ES: 1.07)
Lopes-Silva et al. [30]	10 judo or jiu-jitsu athletes	Elbow flexion and handgrip strength	Number of repetitions in 4 sets of elbow flexion exercise and MVIC in the handgrip strength test	5 mg/kg in capsules ingested 60-minutes pre-exercise	Number of repetitions: ↑ following caffeine ingestion (ES: 0.44) MVIC: ↑ following caffeine ingestion (ES: 0.41)
Muñoz et al. [31]	16 male and 15 female handball players (*n* = 14 AA genotype and *n* = 17 AC/CC genotype; *n* = 6 TT genotype and *n* = 25 CT/CC genotype)	Handgrip strength	MVIC	3 mg/kg in capsules ingested 60-minutes pre-exercise	MVIC: ↔ between conditions or groups
Muñoz et al. [32]	15 elite women handball players	Handgrip strength	MVIC	3 mg/kg in capsules ingested 60-minutes pre-exercise	MVIC: ↑ following caffeine ingestion (ES: 0.35)
Neyroud et al. [33]	21 active men	Electrical stimulations	Evoked force production	6 mg/kg in capsules ingested 45 to 60-minutes pre-exercise	Evoked force production: ↔ between conditions
Nicks & Martin [34]	8 male and 7 female adults	Inspiratory muscle measurements	12 maximal inspiratory maneuvers	5 mg/kg in capsules ingested 60-minutes pre-exercise	Maximal inspiratory pressure: ↑ following caffeine ingestion (ES: 0.22)

					Maximal inspiratory peak pressure: ↑ following caffeine ingestion (ES: 0.20) Maximal rate of pressure development: ↔ between conditions
Norum et al. [35]	15 resistance-trained females (at least 1 year of resistance training experience)	Squat (1RM: 97 ± 13 kg), bench press (1RM: 66 ± 10 kg), and knee extension	1RM, number of repetitions in the bench press and squat at 60% of 1RM, MVIC, torque, and rate of force development	4 mg/kg in capsules ingested 60-minutes pre-exercise	1RM squat: ↑ following caffeine ingestion (ES: 0.27) 1RM bench press: ↑ following caffeine ingestion (ES: 0.18) Number of repetitions (squat): ↑ following caffeine ingestion (ES: 0.27) Number of repetitions (bench press): ↑ following caffeine ingestion (ES: 0.27) MVIC: ↑ following caffeine ingestion (ES: 0.23) Torque: ↔ between conditions Rate of force development: ↔ between conditions
Pereira et al. [36]	29 physically active women (at least 1 year of resistance training experience)	Squat, bench press, leg press, shoulder press, and low-row	Number of repetitions in 3 sets at 10RM	6.5 mg/kg in capsules ingested 60-minutes pre-exercise	↑ following caffeine ingestion in all exercises (ES: 1.33–2.16)
Peterson et al. [37]	15 active men (at least 1 year of resistance training experience)	Knee extension	MVIC, peak torque, and rate of torque development	6 mg/kg in liquid ingested 60-minutes pre-exercise	MVIC: ↔ between conditions Peak torque: ↔ between conditions Rate of torque development: ↑ following caffeine ingestion (ES: 0.57)
Polito et al. [38]	14 resistance-trained men	Chest press, shoulder press, and biceps curl	Number of repetitions in 3 sets at 70% of 1RM	3 or 6 mg/kg in capsules ingested 60-minutes pre-exercise	Number of repetitions: ↑ following caffeine ingestion (both doses) (ES: 0.68–0.74)
Romero-Moraleda et al. [40]	13 female triathlon athletes (at least 6 months of resistance	Half-squat (1RM: 97 ± 17 kg)	Mean and peak velocity at 20%, 40%, 60%, and 80% of 1RM	3 mg/kg in capsules ingested 60-minutes pre-exercise	Mean velocity: ↑ following caffeine ingestion at 60% of 1RM (ES: 0.20–0.30) ↔ between conditions in any other outcomes

	training experience)				
Salatto et al. [41]	15 resistance-trained men (at least 1 year of resistance training experience)	Bench press (1RM: 110 ± 16 kg), incline bench press (1RM: 94 ± 13 kg), and dumbbell bench press (1RM: 44 ± 9 kg)	Average number of repetitions in 3 sets at 80% of 1RM	800 mg in capsules ingested 60-minutes pre-exercise	Number of repetitions (bench press): ↑ following caffeine ingestion (ES: 0.15) Number of repetitions (incline bench press): ↑ following caffeine ingestion (ES: 0.25) Number of repetitions (dumbbell bench press): ↔ between conditions
San Juan et al. [42]	8 male Olympic-level boxers	Handgrip strength	MVIC	6 mg/kg in capsules ingested 75-minutes pre-exercise	MVIC: ↔ between conditions
Santos-Mariano et al. [43]	11 male jumpers and sprinters	Knee extension	MVIC	5 mg/kg in capsules ingested 24, 48, or 72 hours after EIMD	MVIC: ↔ between conditions
Souza et al. [44]	22 resistance-trained men (at least 1 year of resistance training experience)	Knee extension (1RM: 87 ± 16 kg)	Number of repetitions in 3 sets at 30% of 1RM	6 mg/kg in capsules ingested 60-minutes pre-exercise	Number of repetitions: ↑ following caffeine ingestion (ES: 1.19)
Spineli et al. [45]	100 male adolescent athletes (*n* = 49 AA genotype, *n* = 42 AC genotype, *n* = 9 CC genotype; sports: volleyball, athletics, or soccer)	Sit-ups, push-ups, and handgrip strength	Number of repetitions and MVIC in the handgrip strength test	6 mg/kg in capsules ingested 60-minutes pre-exercise	Number of repetitions (sit-ups): ↑ following caffeine ingestion (ES: 0.24); ↔ between groups Number of repetitions (push-ups): ↑ following caffeine ingestion (ES: 0.18); ↔ between groups MVIC: ↔ between conditions or groups

Venier et al. [46]	19 resistance-trained men (at least 1 year of resistance training experience)	Bench press, knee extension and knee flexion	Mean velocity at 50%, 75%, and 90% of 1RM, peak torque and average power	300 mg in caffeinated chewing gum consumed 10-minutes pre-exercise	Mean velocity: ↑ following caffeine consumption at all loads (ES: 0.30–0.44) Peak torque: ↑ following caffeine consumption (ES: 0.22–0.31) Average power: ↑ following caffeine consumption (ES: 0.25–0.30)
Venier et al. [47]	17 resistance-trained men (at least 1 year of resistance training experience)	Bench press, knee extension and knee flexion	Mean velocity at 50%, 75%, and 90% of 1RM, peak torque and average power	300 mg in caffeinated gels ingestion 10-minutes pre-exercise	Mean velocity: ↑ following caffeine ingestion at all loads (ES: 0.33–0.59) Peak torque: ↑ following caffeine ingestion (ES: 0.21–0.37) Average power: ↑ following caffeine ingestion (ES: 0.25–0.31)
Waer et al. [48]	19 middle-aged women	Chair stand and arm curl	Number of repetitions in 30 seconds	100 or 400 mg in capsules ingested 60-minutes pre-exercise	Number of repetitions (chair stand): ↑ following 400 mg of caffeine ingestion (ES: 0.21) Number of repetitions (arm curl): ↑ following 400 mg of caffeine ingestion (ES: 0.27)
Waller et al. [49]	19 physically active females	Knee extension	MVIC and time to maintain 30% or 70% of MVIC	1.5 ± 0.18 mg/kg in capsules ingested 60-minutes pre-exercise	MVIC: ↑ following caffeine ingestion (ES: 0.65) Time to maintain 30% or 70% of MVIC: ↔ between conditions
Wilk et al. [50]	12 resistance-trained men (at least 3 years of resistance training experience)	Bench press (1RM: 129 ± 36 kg)	Peak and mean power and peak and mean velocity during 5 sets of 2 repetitions at 30% of 1RM	3 or 6 mg/kg in capsules ingested 60-minutes pre-exercise	Mean power: ↑ following caffeine ingestion (both doses) (ES: 0.13–0.14) Mean velocity: ↑ following caffeine ingestion (both doses) (ES: 0.73–0.80) Peak power: ↔ between conditions Peak velocity: ↔ between conditions
Wilk et al. [51]	15 resistance-trained men (at least 3 years of resistance training experience)	Bench press (1RM: 122 ± 25 kg)	Peak and mean power and peak and mean velocity during 3 sets of 5	3, 6, or 9 mg/kg in capsules ingested 60-minutes pre-exercise	↔ between conditions in any of the analyzed outcomes

			repetitions at 50% of 1RM		
Wilk et al. [53, 54]	16 resistance-trained men (at least 3 years of resistance training experience)	Bench press (1RM: 118 ± 15 kg)	1RM, number of repetitions at 50% of 1RM, time under tension, peak and mean power and peak and mean velocity	9 or 11 mg/kg in capsules ingested 60-minutes pre-exercise	1RM: ↑ following caffeine ingestion (both doses) (ES: 0.26–0.45) Mean power, peak power, and peak velocity: ↓ following caffeine ingestion (ES: 0.38–0.84) ↔ between conditions in any other outcomes
Wilk et al. [55]	20 resistance-trained men (at least 2 years of resistance training experience)	Bench press (1RM: 102 ± 9 kg)	Number of repetitions at 70% of 1RM, time under tension, peak and mean power and peak and mean velocity	5 mg/kg in capsules ingested 60-minutes pre-exercise	Time under tension: ↓ following caffeine ingestion (ES: 0.11) Mean eccentric velocity: ↑ following caffeine ingestion (ES: 1.18) ↔ between conditions in any other outcomes

MVIC: maximal voluntary isometric contraction; RM: repetition maximum; EIMD: exercise-induced muscle damage; ES: effect size; ↔ no significant differences; ↓ significant decrease; ↑ significant increase; [a]data are presented as mean ± standard deviation