Acute Effects of Caffeine Supplementation on Movement Velocity in Resistance Exercise: A Systematic Review and Meta-analysis

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Acute effects of caffeine supplementation on movement velocity in resistance exercise: a systematic review and meta-analysis

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Abstract

Background: Several studies investigated the effects of caffeine supplementation on movement velocity in resistance exercise. However, these studies presented inconsistent findings.

Objective: This paper aimed to: (a) review the studies that explored the effects of caffeine supplementation on movement velocity in resistance exercise; and (b) pool their results using a meta-analysis.

Methods: A search for studies was performed through seven databases. Random-effects meta-analyses of standardized mean differences (SMD) were performed to analyze the data. Sub-group meta-analyses explored the effects of caffeine on different velocity variables (i.e., mean vs. peak velocity), different loads (i.e., low, moderate, and high loads), and upper and lower-body exercises.

Results: Twelve studies met the inclusion criteria. In the main meta-analysis, in which we pooled all available studies, the SMD favored the caffeine condition (SMD = 0.62; 95% confidence interval [CI]: 0.39–0.84; p<0.001). Sub-group analyses indicated that caffeine significantly enhances mean (SMD = 0.80; 95% CI: 0.48–1.12; p<0.001) and peak velocity (SMD = 0.41; 95% CI: 0.08–0.75; p=0.014), movement velocity with low loads (SMD = 0.78; 95% CI: 0.41–1.14; p<0.001), moderate loads (SMD = 0.58; 95% CI: 0.25–0.91; p=0.001), and high loads (SMD = 0.70; 95% CI: 0.33–1.07; p<0.001), as well as in lower-body (SMD = 0.82; 95% CI: 0.42–1.23; p<0.001) and upper-body exercises (SMD = 0.59; 95% CI: 0.37–0.82; p<0.001).

Conclusion: Acute caffeine supplementation is highly ergogenic for movement velocity in resistance exercise. Sub-group analyses indicated that caffeine ingestion is ergogenic: (a) for both mean and peak velocity; (b) for movement velocity when exercising with low, moderate and high loads, and (c) for movement velocity in both lower and upper-body exercises.

Previous meta-analyses that explored the effects of caffeine on various aspects of resistance exercise performance (i.e., muscular strength and endurance) reported trivial to moderate ergogenic effects (effect size range: 0.16–0.38). In the present meta-analysis, the pooled effect size ranged from 0.41–0.82. From a resistance exercise performance standpoint, this suggests that caffeine has the most pronounced performance-enhancing effects on movement velocity.

Key points

a) Acute caffeine supplementation seems to be highly ergogenic for movement velocity in resistance exercise.

b) Ergogenic effects of caffeine were found for both mean and peak velocity, movement velocity when exercising with low, moderate and high loads, and in both lower and upper-body exercises.

1 Introduction

The 2018 International Olympic Committee consensus statement classified caffeine as a nutritional supplement that has good evidence of benefits for enhancing exercise performance [1]. As such, caffeine is widely consumed by athletes [2]. Studies that examined the prevalence of caffeine ingestion among different groups of athletes reported that those competing in strength and power-based sports are among the highest users of caffeine—in terms of the urine concentration of caffeine [2].

Many primary studies and several meta-analyses have explored the effects of caffeine on muscle strength [3–10]. The currently published meta-analyses investigated the effects of caffeine on one-repetition maximum (1RM), isokinetic, and isometric strength [3–5]. These meta-analyses [3–5] reported ergogenic effects of caffeine on strength in the effect size magnitude of 0.16 for isokinetic strength (95% confidence interval [CI]: 0.06–0.26), 0.19 for isometric strength (95% CI: 0.09–0.29), and 0.20 for 1RM strength (95% CI: 0.03–0.36), respectively. These effects are considered to be of small or trivial magnitudes.

A recent review suggested that caffeine's effects might be greater on movement velocity (i.e., a form of power expression) than on maximal muscle strength [10]. In resistance exercise, movement velocity is often assessed by using tools that measure barbell speed (such as linear position transducers). These tools can provide a full load-velocity profile (i.e., performance at different percentages of the 1RM) which is relevant when it comes to caffeine supplementation given that the effects of caffeine might not be uniform across different external loads [10]. Furthermore, this is important if we consider that resistance training is commonly performed with sub-maximal loads, whereas maximal strength expression in the practical context is not as frequent. Finally, velocity-based measures provide both mean velocity (the average velocity from the start of the concentric phase until the bar reaches the maximum height) and peak velocity data (maximum velocity reached during the concentric phase) and both variables are relevant to athletes [11].

Several recent studies have investigated the effects of caffeine supplementation on movement velocity in resistance exercise [12–23]. However, these studies presented inconsistent findings [12–23]. Therefore, this paper aimed to: (a) review the studies that explored the effects of caffeine supplementation on movement velocity in resistance exercise; (b) pool their results using a meta-analysis; and (c) provide additional context to this topic by focusing on potential moderating study characteristics such as the effects of caffeine on different velocity variables (i.e., mean and peak velocity), the effects of caffeine on movement velocity with different external loads, and the effects of caffeine in upper vs. lower-body exercises.

2 Methods

The present review was carried out following the recommendations and criteria established in the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) statement guidelines [24].

2.1 Search strategy

For this systematic review, searches were performed through Networked Digital Library of Theses and Dissertations, Open Access Theses and Dissertations, ProQuest Dissertation & Theses, PubMed/MEDLINE, Scopus, SPORTDiscus, and Web of Science (including all Web of Science Core Collection: Citation Indexes) databases. The search syntax included the following keywords coupled with Boolean operators: "caffeine" AND ("mean velocity" OR "peak velocity" OR "resistance exercise" OR "resistance training" OR "strength exercise" OR "strength training" OR "bench press" OR "speed" OR "mean power" OR "peak power" OR "squat" OR "leg press" OR "leg extension" OR "ballistic"). No year restriction was applied in the search. Secondary searches included: (a) screening the reference lists of all included studies and relevant review papers [3–5, 10]; (b) examining the studies that cited the included studies (i.e., forward citation tracking) through Google Scholar. Three authors (JRG, RD, and JG) independently performed the searches; any discrepancies between the authors in the study selection were resolved in consultation with a fourth reviewer (DC). The search was performed on April 9th, 2019.

2.2 Inclusion criteria

Studies meeting the following criteria were included: (a) an experimental trial published in English; (b) included humans without chronic disease or injury as study participants; (c) utilized a single or double-blind crossover design with at least one placebo and one caffeine trial; and (d) assessed the effects of caffeine ingestion in any dose and form (as long as the effects of caffeine could be isolated) on movement velocity during resistance exercise. We considered only studies in which the assessment of movement velocity included the same load/same number of repetitions in the placebo and caffeine conditions. When required, corresponding authors from the included studies were contacted to provide the required data.

Publication bias may occur due to the “file drawer” syndrome which suggests that studies with significant and larger effects sizes are more likely to be published than studies that report small or non-statistically significant results [25]. Therefore, the inclusion of only published studies may bias the pooled results [25]; to avoid this, we included studies published in peer-reviewed journals as well as theses, dissertations, and conference abstracts.

2.3 Study coding and data extraction

The following data were extracted from the included studies: (a) study design; (b) sample characteristics (including age, sex, sample size, and training status); (c) dose, form, and timing of caffeine ingestion; (d) exercises, loads, and velocity variables used for the testing; (e) main findings from the caffeine and placebo conditions. Data extraction was performed independently by three authors (JRG, DC, and JG).

2.4 Methodological quality

The methodological quality of the included studies was assessed using the "*Tool for the assEssment of Study qualiTy and reporting in EXercise*" (TESTEX) [26]. The full details regarding the TESTEX scale can be found elsewhere [26]. The TESTEX scale has 12 items divided into two sections referring to study quality (items 1 to 5) and study reporting (items 6 to 12). This checklist represents a modified version of the PEDro scale [27] adjusted for studies in sport and exercise science. Even though the TESTEX scale does not consider blinding of participants or therapists, blinding is an essential component of studies in the sports nutrition line of research [1]. Therefore, we modified the TESTEX scale and included two additional items (item 5 and 6 on the modified version) that refer to the blinding of participants and therapists, respectively. With this adjustment, the scale included a total of 14 items.

Each question is answered with "yes" if the criteria are satisfied or with a "no" if the criteria are not satisfied; only the answer "yes" corresponds to one point. In item 8, there are three questions and each of them can be scored with a point equating to a maximum number of three points. Similarly, in item 10, the maximum number of points is two. The maximal number of points that can be scored on the whole checklist is 17. Based on the summary score, the methodological quality of the included studies was categorized as follows: excellent quality (15–17 points), good quality (12–14 points), fair quality (9–11 points), or poor quality (<9 points). The methodological quality appraisal was independently performed by three authors (JRG, ARF, and JG); discrepancies between the authors were resolved in consultation with a fourth reviewer (DC). We contacted the corresponding authors of the included studies when a clarification on certain aspects of the study design was needed.

2.5 Statistical analyses

A random-effects meta-analysis was performed using the statistical software STATA 14 (Stata Corp., College Station, TX, USA). Standardized mean differences (Hedge's g [SMD]) and 95% CIs were calculated between the placebo and caffeine trials based on the exercise performance mean and standard deviation data, the correlation between the trials, and the number of participants. Given that none of the included studies reported correlation values, a conservative 0.5 correlation was assumed for all studies [28]. The SMD magnitude was interpreted as: (a) trivial (<0.20); (b) small (0.20–0.49); (c) moderate (0.50–0.79); and (d) large (≥0.80) [29]. The statistical significance threshold was set at $p < 0.05$.

In the main analysis, we pooled all available data. This included combining mean and peak velocity data, values obtained with different external loads, as well as values obtained using upper and lower-body exercises. In this analysis, when a study measured movement velocity under multiple conditions, such as multiple loads, SMDs and variances were calculated for each outcome separately, and average SMD and variance values were used for the analysis. Sub-group analyses explored the effects of caffeine on different velocity variables (i.e., mean and peak velocity), different loads (i.e., low, moderate, and high), and upper and lower-body exercises. In the sub-group analysis for different loads, low load was considered as <30%

1RM, moderate load was between 30% and 70% 1RM, and high load was from 70% to 100% 1RM [30, 31]. In a sensitivity analysis, the pooled results were examined after excluding the unpublished studies included in the review [15, 21, 23]. Heterogeneity was measured using the I^2 statistic. I^2 values lower than 50% indicated low heterogeneity, I^2 values from 50% to 75% indicated moderate heterogeneity and I^2 values >75% indicated a high level of heterogeneity.

We also calculated 95% prediction intervals (95% PI) for each analysis by using the number of included studies, the pooled standardized mean difference (SMD), the upper limit of the 95% CI, and the tau-squared values. The 95% PI represents the range in which the SMD of a future study conducted on the topic will most likely be.

3 Results

3.1 Search results

The number of search results was 2423. A total of 2400 search results were excluded based on their titles and/or abstracts and 23 full-text articles were read. Fourteen articles were excluded from the review because they did not examine the effects of caffeine on movement velocity or because they presented duplicate data. Nine studies were initially included; however, three additional studies were found through the secondary searches, and therefore, a total of 12 studies were included in the review [12–23; Figure 1]. Nine papers were published in peer-reviewed journals while three are conference abstracts.

3.2 Descriptive characteristics of the studies

The included studies are summarized in Table 1. All studies utilized a randomized, double-blind design. In three instances, movement velocity data were reported in separate papers, even though they were collected in the same sample of participants (Table 1). The total sample size across all studies was 151 participants. Seven studies included only males, four included both males and females, and one study included only females. All studies were conducted in young adults. Only in one study, the participants were classified as athletes while in the remaining studies, they were considered as resistance-trained or recreationally active. In the studies that provided caffeine doses per kilogram of body weight, the doses ranged from 1 to 9 mg·kg^{-1}. In the studies that provided absolute doses, the caffeine dose ranged from 150 to 328 mg.

3.3 Meta-analysis results

In the main meta-analysis, the pooled effect favored the caffeine condition (SMD = 0.62; 95% CI: 0.39–0.84; $p < 0.001$; $I^2 = 0.0\%$; 95% PI: 0.34–0.88 [Figure 2]).

3.3.1 Effects of caffeine on mean and peak velocity

Sub-group meta-analysis indicated that caffeine significantly enhances mean movement velocity (SMD = 0.80; 95% CI: 0.48–1.12; $p < 0.001$; $I^2 = 0.0\%$; 95% PI: 0.28–1.32 [Figure 3]) and peak movement velocity (SMD = 0.41; 95% CI: 0.08–0.75; $p = 0.014$; 95% $I^2 = 24.7\%$; PI: –0.33 to 1.15 [Figure 3]).

3.3.2 Effects of caffeine on movement velocity with low, moderate, and high-loads

Sub-group meta-analysis indicated that caffeine significantly improves movement velocity with low loads (SMD = 0.78; 95% CI: 0.41–1.14; $p < 0.001$; 95% $I^2 = 0.0\%$; 95% PI: 0.17–1.37 [Figure 4]), moderate loads (SMD = 0.58; 95% CI: 0.25–0.91; $p = 0.001$; $I^2 = 0.0\%$; 95% PI: 0.04–1.11; [Figure 4]), and high loads (SMD = 0.70; 95% CI: 0.33–1.07; $p < 0.001$; $I^2 = 40.3\%$; 95% PI: –0.26 to 1.66; [Figure 4]).

3.3.3 Effects of caffeine on movement velocity in upper- and lower-body exercises

Sub-group meta-analysis indicated that caffeine significantly improves movement velocity in lower-body exercises (SMD = 0.82; 95% CI: 0.42–1.23; $p < 0.001$; $I^2 = 0.0\%$; 95% PI: –0.08 to 1.72; [Figure 5]) and upper-body exercises (SMD = 0.59; 95% CI: 0.37–0.82; $p < 0.001$; $I^2 = 0.0\%$; 95% PI: 0.32–0.86; [Figure 5]).

3.3.4 Sensitivity analysis results

The results from the sensitivity analyses are reported in Table 2. The exclusion of the unpublished studies only changed the effect for peak velocity from being significant ($p < 0.05$) to non-significant ($p > 0.05$); the exclusion of these studies did not impact the results of any other analysis.

3.4 Methodological quality

The average score on the TESTEX scale was 14, with the values from individual studies ranging from 13 to 15. Four studies were categorized as being of excellent methodological quality, and eight studies were categorized as being of good quality. Individual scores for the quality assessment can be found in Table 3.

4 Discussion

The main finding of this review is that caffeine is ergogenic for movement velocity in resistance exercise. These ergogenic effects were found for both mean and peak velocity. Additionally, performance-enhancing effects of caffeine were found when exercising with low, moderate, and high loads, and in both upper as well as lower-body exercises. All included studies had a double-blind design and were categorized as being of good or excellent methodological quality, which therefore strengthens these conclusions.

In resistance exercise, previous meta-analyses established that caffeine ingestion acutely enhances muscular strength (SMD range: 0.16–0.20), and muscular endurance (SMD range: 0.28–0.38) [3–5, 32, 33]. In the present review, the pooled effect sizes ranged from 0.41–0.82. Based on this comparison of effect sizes between meta-analyses, from a resistance exercise performance standpoint, it seems that caffeine has the most pronounced ergogenic effects on movement velocity. This notion also has a substantial physiological support given that caffeine may: (a) increase motor unit recruitment, muscle fiber conduction velocity, and voluntary activation [34]; (b) increase the rate of calcium release from the sarcoplasmic reticulum [35]; and (c) may directly potentiate skeletal muscle power output—as shown by studies using isolated muscle fibers [36]. All these physiological responses to caffeine ingestion may result in a more forceful muscular contraction and make caffeine very conducive for increasing movement velocity.

An interesting finding of this review is that caffeine's effects seem to be higher for mean as compared to peak velocity (SMD of 0.80 and 0.41, respectively). Most studies included in this analysis measured either mean or peak velocity. In other words, there is a lack of studies exploring the effects of caffeine on both velocity variables in the same groups of participants. This aspect is important to emphasize given the considerable inter-individual variation in responses to caffeine ingestion as it pertains to its effects on exercise performance [37, 38]. Future studies on this topic may consider measuring both mean and peak velocity in the same sample to explore if the magnitude of caffeine's effects indeed differs between these two velocity variables.

The use of velocity-based measures in resistance exercise allows the assessment of a full load-velocity profile. It is important to establish the effects of caffeine ingestion on movement velocity across a wide range of loading zones given that: (a) low loads are optimal for power development in the bench press throw and squat jump exercise; (b) moderate loads are considered as ideal for power development in the bench press and squat exercise; and (c) high loads seems to result in the greatest peak power production in the power clean and hang power clean exercises [30, 31]. The results obtained in the present review indicate that the SMDs for the effects of caffeine on movement velocity are similar regardless of the external load. Therefore, regardless of the loads used in the exercise session, individuals interested in acutely enhancing movement velocity in resistance exercise may consider supplementing with caffeine pre-exercise.

Previous meta-analyses have observed that the effects of caffeine on strength are not uniform between the upper and lower-body musculature [4, 5]. In the meta-analysis by Warren et al. [4], a significant effect of caffeine on isometric strength was found in the lower but not upper-body musculature. In contrast to these findings, Grgic et al. [5] reported that caffeine ingestion enhances 1RM strength in the upper but not lower-body musculature. However, our results suggest that caffeine may be similarly effective for both upper-body (SMD: 0.59; 95% CI: 0.37–0.82) and lower-body musculature (SMD: 0.82; 95% CI: 0.42–1.23). These results are different from previous meta-analyses likely because the physiological mechanism(s) that underpin caffeine’s ergogenic effects on strength are different from those that are responsible for the performance-enhancing effects on movement velocity. Future studies are warranted to explore the reasons for these divergent findings.

4.1 Sensitivity analysis: the influence of unpublished studies

Besides the main meta-analyses, we also performed sensitivity analyses in which we explored the influence of studies that were included in the review but were not published in peer-reviewed journals [15, 21, 23]. When excluding these three studies, the pooled SMDs generally did not change (Table 2), and these results suggest that the inclusion of unpublished studies did not over or underestimate the pooled effect size. The only difference was found in the analysis for peak velocity; in this analysis, the exclusion of unpublished studies resulted in a change from a significant to a non-significant effect. However, this might have been caused by the lack of included studies, as the sensitivity analysis for this outcome included only three studies.

4.2 Practical implications

Generally, the main goal of strength and power resistance exercise programs is to move the force-velocity curve to the right resulting with athletes being able to lift heavier loads at higher velocities [39]. Our findings indicate that the consumption of caffeine before exercise may acutely increase movement velocity, therefore, increasing training intensity. Given these acute findings, it is plausible that the use of caffeine before each exercise session may also enhance training adaptations; however, future long-term studies are needed to establish such effects. The results also indicate that the use of caffeine should be standardized (i.e., used in the same fashion or restricted altogether) before testing sessions that include the assessment of movement velocity. This may be especially important when attempting to determine the efficacy of a given training program or when exploring the reliability of a given device used for measuring movement velocity.

Individuals interested in supplementing with caffeine should consider that the ingestion of this supplement may be associated with side-effects such as anxiety, insomnia, increased heart rate, and others (Table 1). These side-effects seem to increase with the dose of caffeine linearly [20]; thus, their occurrence may be minimized by using smaller doses of caffeine (<3 $mg \cdot kg^{-1}$), as such doses may also provide ergogenic effects and are associated with fewer side-effects [7, 40].

4.3 Methodological quality

As assessed using the TESTEX checklist, the included studies are classified as being of good or excellent methodological quality. However, we noted one methodological limitation specific to studies focusing on sports supplements in the majority of the included studies. Out of the twelve included studies, only Venier et al. [22] explored the effectiveness of the blinding of participants to the caffeine and placebo conditions. In this study, when examined pre-exercise, 78% and 32% of participants correctly identified the placebo and caffeine conditions beyond random chance, respectively. Post-exercise, for the placebo and caffeine conditions, these values amounted to 63% and 53%, respectively. The efficacy of the blinding is relevant to highlight given the recent findings that correct supplement identification may influence an outcome of a given exercise task and therefore, present a source of bias in the sports nutrition line of research [41]. This methodological aspect should be adequately explored and addressed in future studies to increase the robustness of the presented findings.

4.4 Limitations

There are several limitations of this review that need to be acknowledged. One such limitation is that only one study included athletes as study participants, whereas the majority of other studies included resistance-trained individuals. Additionally, the number of female participants was small, as only one study included an only female sample [17]. Therefore, future research among athletes and females is warranted to increase the generalizability of the findings to these populations.

While our results support that caffeine ingestion may increase movement velocity, we were not able to determine the “optimal” dose for these performance-enhancing effects. The included studies used a wide range of doses (i.e., from 1 to 9 $mg \cdot kg^{-1}$) and future dose-response studies are needed to explore what doses provide the greatest improvements in performance while minimizing the occurrence and severity of side-effects.

5 Conclusion

Based on the results of this review, acute caffeine supplementation is highly ergogenic for movement velocity in resistance exercise. Sub-group analyses indicated that caffeine ingestion is ergogenic for both mean and peak velocity. The ergogenic effects of caffeine on movement velocity were significant when exercising with low, moderate, and high loads as well as in lower-body and upper-body exercises. Therefore, individuals interested in the acute enhancement of movement velocity in resistance exercise may consider supplementing with caffeine pre-exercise.

Compliance with Ethical Standards

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Conflict of interest

Javier Raya-González, Tara Rendo-Urteaga, Raúl Domínguez, Daniel Castillo, Alejandro Rodríguez-Fernández and Jozo Grgic declare that they have no conflicts of interest relevant to the content of this review.

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Figure 1. Flow diagram of the study retrieval process

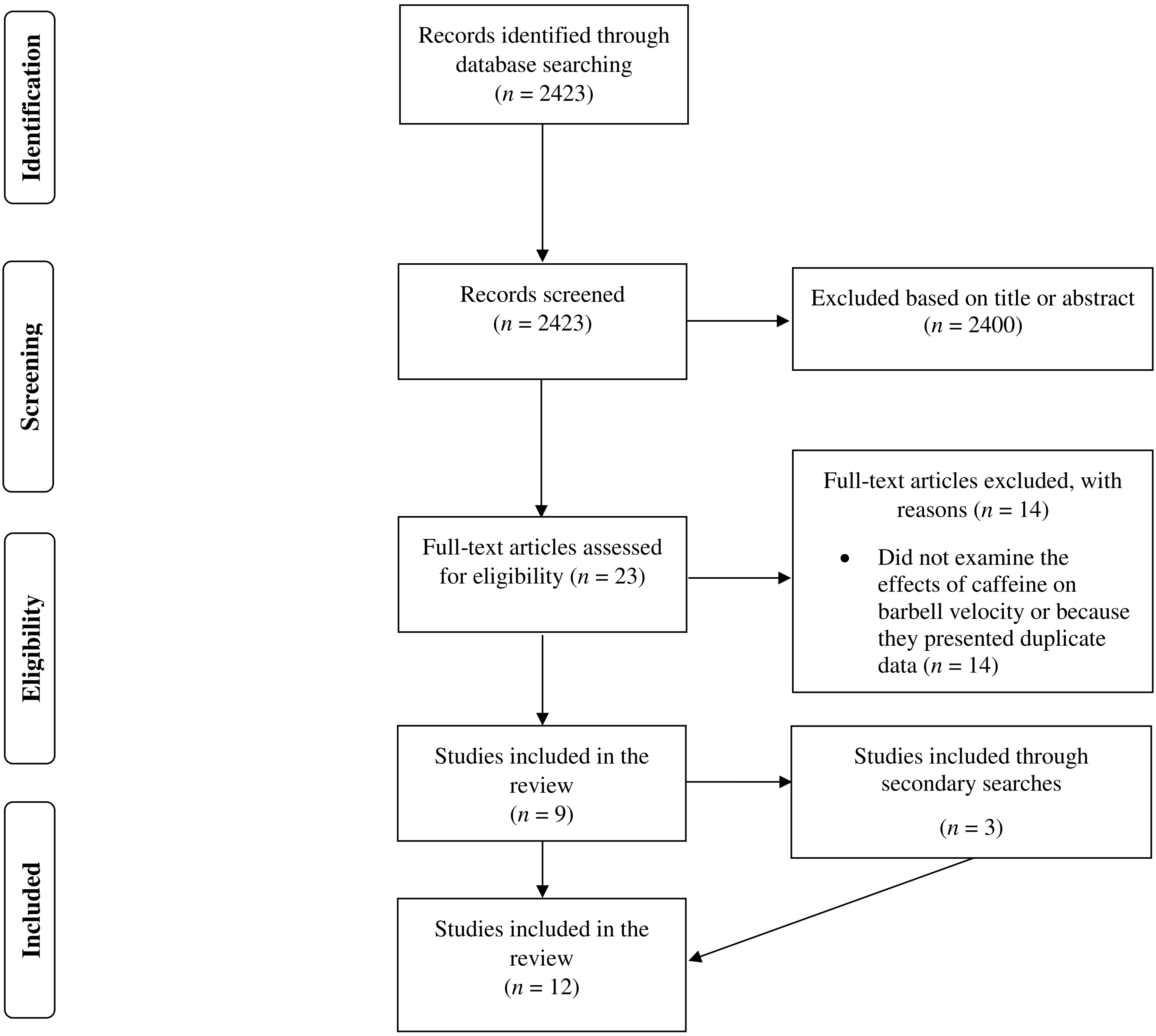


Figure 2. Results of the meta-analysis on the effect of caffeine supplementation on movement velocity. The numbers on the x-axis denote the standardized mean differences (Std. Mean Difference) expressed as Hedge's g between the caffeine and placebo trials; the horizontal lines denote the respective 95% confidence intervals (CI).

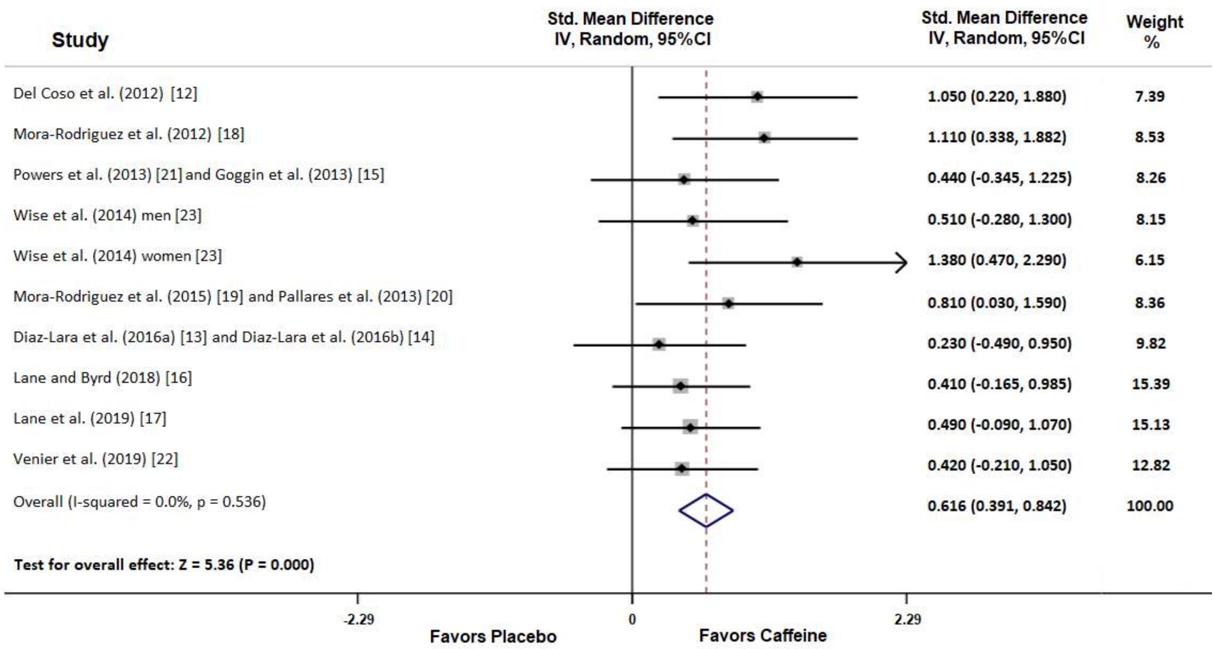
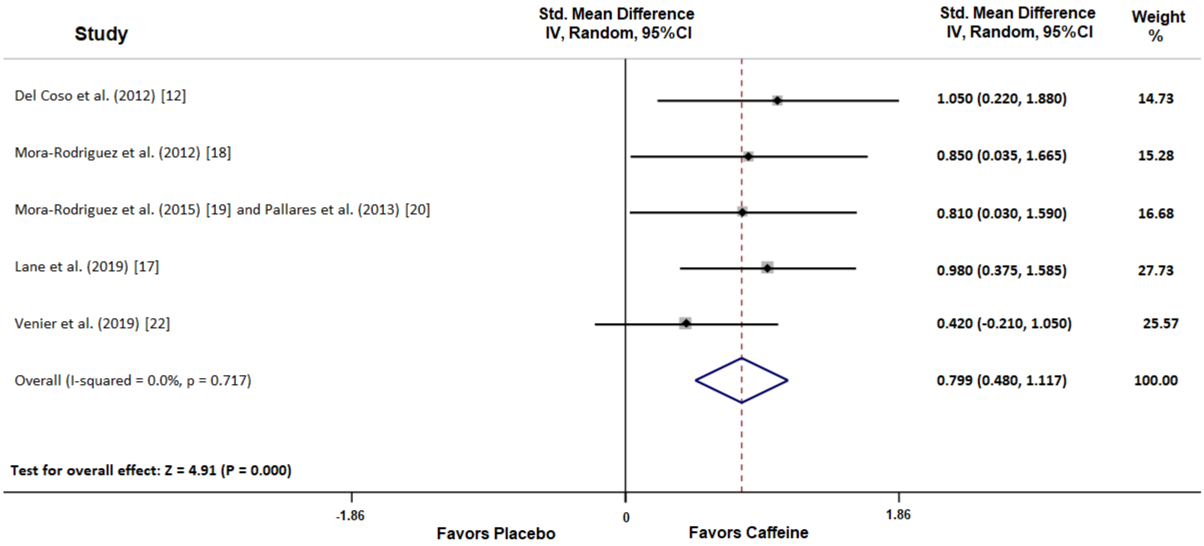


Figure 3. Results of the meta-analysis on the effect of caffeine supplementation on mean movement velocity (upper section) and peak movement velocity (lower section). The numbers on the x-axis denote the standardized mean differences (Std. Mean Difference) expressed as Hedge's g between the caffeine and placebo trials; the horizontal lines denote the respective 95% confidence intervals (CI).



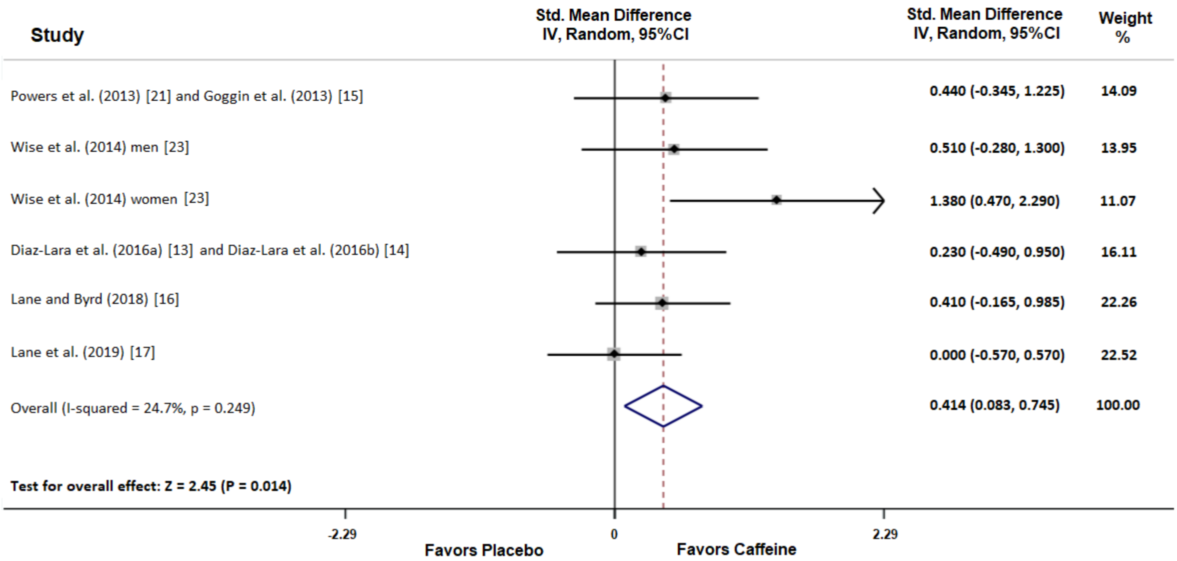


Figure 4. Results of the meta-analysis on the effect of caffeine supplementation on movement velocity with low loads (upper section), moderate loads (middle section), and high loads (lower section). The numbers on the x-axis denote the standardized mean differences (Std. Mean Difference) expressed as Hedge's g between the caffeine and placebo trials; the horizontal lines denote the respective 95% confidence intervals (CI).

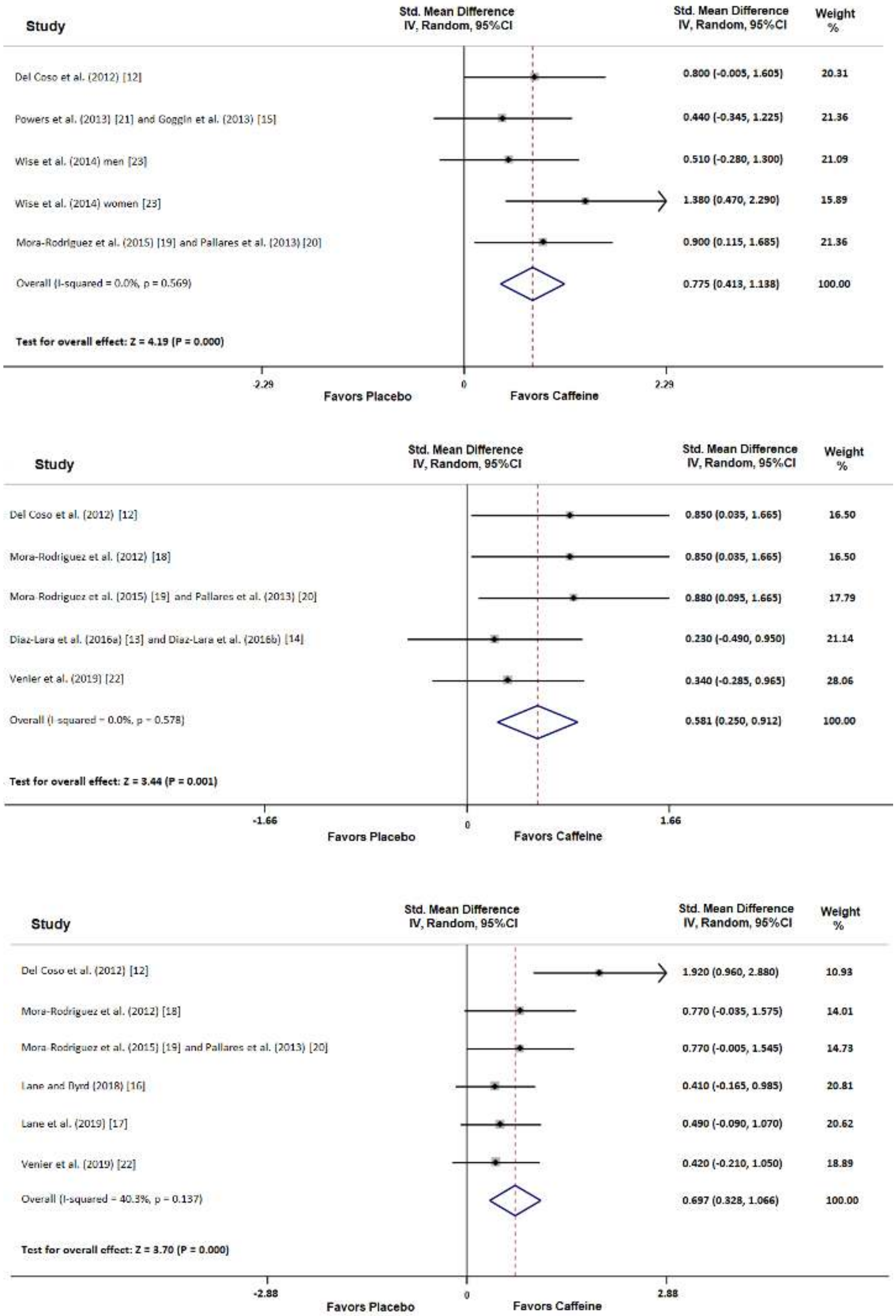


Figure 5. Results of the meta-analysis on the effect of caffeine supplementation on movement velocity in lower-body (upper section) and upper-body (lower section) exercises. The numbers on the x-axis denote the standardized mean differences (Std. Mean Difference) expressed as Hedge's g between the caffeine and placebo trials; the horizontal lines denote the respective 95% confidence intervals (CI).

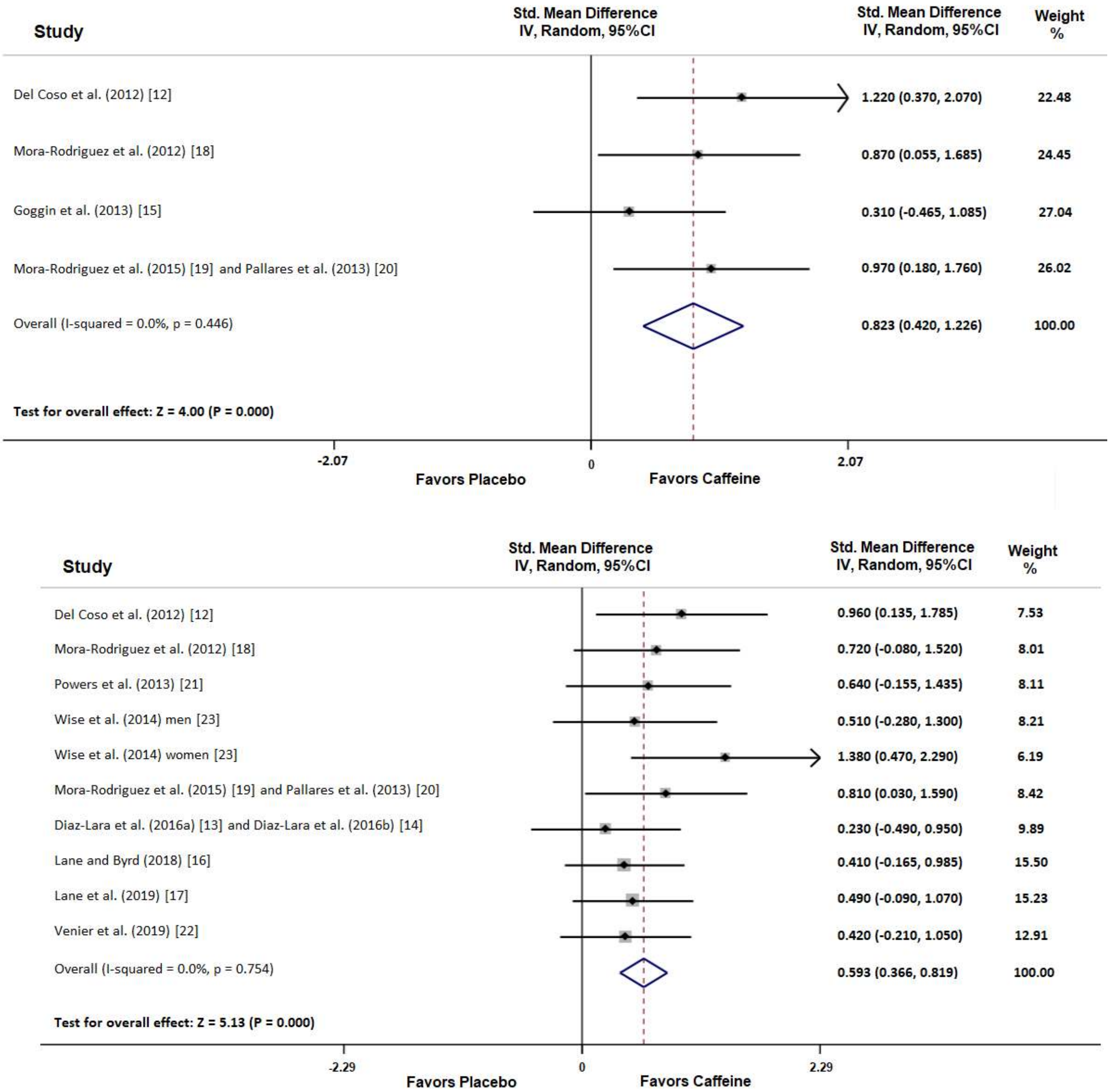


Table 1. Summary of the studies included in the review

Reference	Study design	Participants characteristics	Training status	Protocol of caffeine supplementation	Velocity outcomes	Load	Resistance exercises	Reported side-effects
Del Coso et al. (2012) [12]	RDB	9 men and 3 women (age: 30 ± 7 years)	Recreationally active	1 and 3 $mg \cdot kg^{-1}$ in an energy drink ingested 60 minutes pre-exercise[a]	Mean velocity	From 10% to 100% 1RM (10% increments)	Half-squat and bench press	Increased vigor/activeness with 3 $mg \cdot kg^{-1}$ as compared to placebo
Diaz-Lara et al. (2016a) [13] and Diaz-Lara et al. (2016b) [14][b]	RDB	14 men (age: 29 ± 3 years)	BJJ athletes	3 $mg \cdot kg^{-1}$ in capsules ingested 60 minutes pre-exercise	Peak velocity	45% 1RM	Bench press	No significant difference between the caffeine and placebo in any of the assessed side-effects
Goggin et al. (2013) [15] and Powers et al. (2013) [21][b]	RDB	7 men and 5 women (age: 23 ± 5 years)	Resistance-trained	328 mg of caffeine in instant Via® coffee ingested 30-90 minutes pre-exercise[c]	Peak velocity	30% 1RM for both exercises	Bench press and squat	None reported
Lane and Byrd (2018) [16]	RDB	23 men (age: 23 ± 4 years)	Recreationally active	300 mg of caffeine ingested 25 minutes pre-exercise	Peak velocity	80% 1RM	Bench press	None reported
Lane et al. (2019) [17]	RDB	23 women (age: 23 ± 4 years)	Recreationally active	150 mg of caffeine ingested 25 minutes pre-exercise	Mean and peak velocity[d]	80% 1RM	Bench press	None reported
Mora-Rodriguez et al. (2012) [18]	RDB	12 men (age: 20 ± 3 years)	Resistance-trained	3 $mg \cdot kg^{-1}$ in capsules ingested 60 minutes pre-exercise	Mean velocity	75% 1RM and loads that elicited a velocity of 1 $m \cdot s^{-1}$	Bench press and squat	Slight increase in the incidence of gastrointestinal problems and urinary excretion with caffeine ingestion

Mora-Rodriguez et al. (2015) [19] and Pallares et al. (2013) [20][b]	RDB	13 men (age: 22 ± 3 years)	Resistance-trained	3, 6, and 9 $mg \cdot kg^{-1}$ in capsules ingested 60 minutes pre-exercise	Mean velocity	25%, 50%, 75%, and 90% 1RM	Bench press and squat	Side-effects increased linearly with the dose of caffeine; dose of 9 $mg \cdot kg^{-1}$ resulted with a high incidence of side-effects such as insomnia, muscle soreness, increased urine output, etc.
Venier et al. (2019) [22]	RDB	19 men (age: 24 ± 5 years)	Resistance-trained	300 mg of caffeine in chewing gum consumed 10 minute pre-exercise	Mean velocity	50%, 75%, and 90% 1RM	Bench press	No significant difference between the caffeine and placebo in any of the assessed side-effects
Wise et al. (2014) [23]	RDB	12 men and 11 women (age: 2 ± 4 years)	Resistance-trained	328 mg of caffeine in instant Via® coffee ingested 30-90 minutes pre-exercise[c]	Peak velocity	30% 1RM	Bench press	None reported

RDB: randomized double-blind; 1RM: one repetition maximum; BJJ: Brazilian jiu-jitsu
age is reported as mean ± standard deviation
[a] the only difference between the placebo and energy drink conditions was the amount of caffeine
[b] the studies included the same participants even though the data was reported in two different papers
[c] the only difference between the placebo and instant Via® coffee conditions was the amount of caffeine
[d] only peak velocity data was reported in the paper

Table 2. Sensitivity analyses results

Analysis	Excluded studies	Pooled effect size and 95% CI	p-value
Main meta-analysis	Powers et al. (2013) [21] and Goggin et al. (2013) [15], and Wise et al. (2014) [23]	0.59 (0.33, 0.84)	$p < 0.001$
Meta-analysis on the effects of caffeine on peak velocity	Powers et al. (2013) [21] and Goggin et al. (2013) [15], and Wise et al. (2014) [23]	0.21 (-0.14, 0.56)	$p = 0.244$
Meta-analysis on the effects of caffeine on movement velocity with low loads	Powers et al. (2013) [21] and Goggin et al. (2013) [15], and Wise et al. (2014) [23]	0.85 (0.29, 1.41)	$p = 0.003$
Meta-analysis on the effects of caffeine on movement velocity in lower-body exercises	Goggin et al. (2013) [15]	1.01 (0.54, 1.48)	$p < 0.001$
Meta-analysis on the effects of caffeine on movement velocity in upper-body exercises	Powers et al. (2013) [21] and Wise et al. (2014) [23]	0.53 (0.28, 0.79)	$p < 0.001$
CI: confidence interval			

Table 3. Results from the modified Tool for the assEssment of Study qualiTy and reporting in EXercise (TESTEX) quality assessment scale

Study	Items														Total
	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Item 13	Item 14	
Del Coso et al. (2012) [12]	1	0	0	1	1	1	1	3	1	2	1	1	1	1	15
Diaz-Lara et al. (2016a) [13] and Diaz-Lara et al. (2016b) [14][a]	1	0	0	1	1	1	1	3	1	2	1	1	1	1	15
Goggin et al. (2013) [15] and Powers et al. (2013) [21][a]	0	0	0	1	1	1	1	2	1	2	1	1	1	1	13
Lane and Byrd (2018) [16]	1	0	0	1	1	1	1	2	1	1	1	1	1	1	14
Lane et al. (2019) [17]	1	0	0	1	1	1	1	2	1	2	1	1	1	1	14
Mora-Rodriguez et al. (2012) [18]	0	0	0	1	1	1	1	3	1	2	1	1	1	1	14
Mora-Rodriguez et al. (2015) [19] and Pallares et al. (2013) [20][a]	0	0	0	1	1	1	1	3	1	2	1	1	1	1	14
Venier et al. (2019) [22]	1	0	0	1	1	1	1	3	1	2	1	1	1	1	15
Wise et al. (2014) [23]	0	0	0	1	1	1	1	2	1	2	1	1	1	1	13

[a]the studies included the same participants even though the data was reported in two different papers