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Moderators of Caffeine's Effects on Jumping Performance in Females: A Systematic Review and Meta-Analysis

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ABSTRACT

We aimed to perform a systematic review and meta-analysis of caffeine's effects on vertical jumping performance in females, with subgroup analyses for potential moderators, including phase of the menstrual cycle, testing time of day, caffeine dose, and test type. Fifteen studies were included in the review (n = 197). Their data were pooled in a random-effects meta-analysis of effect sizes (Hedges' g). In the main meta-analysis, we found an ergogenic effect of caffeine on jumping performance (g: 0.28). An ergogenic effect of caffeine on jumping performance was found when the testing was carried out in the luteal phase (g: 0.24), follicular phase (g: 0.52), luteal or follicular phase (g: 0.31), and when the phase was not specified (g: 0.21). The test for subgroup differences indicated that the ergogenic effects of caffeine were significantly greater in the follicular phase compared to all other conditions. An ergogenic effect of caffeine on jumping performance was found when the testing was carried out in the morning (g: 0.38), evening (g: 0.19), mixed morning or evening (g: 0.38), and when time was not specified (g: 0.32), with no subgroup differences. An ergogenic effect of caffeine on jumping performance was found when the dose was ≤3 mg/kg (g: 0.21), or >3 mg/kg (g: 0.37), with no subgroup differences. An ergogenic effect of caffeine on jumping performance was found in the countermovement jump test (g: 0.26) and squat jump test (g: 0.35), with no subgroup differences. In summary, caffeine ingestion is ergogenic for vertical jumping performance in females, and it seems that the magnitude of these effects is the largest in the follicular phase of the menstrual cycle.

KEY TEACHING POINTS

- In the main meta-analysis, which included 15 studies and ~200 participants, we found a small but very precise ergogenic effect of caffeine on vertical jumping performance in females.
- In a subgroup analysis for phase of the menstrual cycle, the ergogenic effects of caffeine on jumping performance were the largest in the follicular phase.
- An ergogenic effect of caffeine was consistently found in analyses for testing time of day (morning, evening, mixed morning or evening, or not specified), caffeine dose (≤3 mg/kg or >3 mg/kg) and test type (squat or countermovement jump).

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Introduction

Caffeine is an ergogenic aid commonly used among athletes and non-athletes (1). The International Olympic Committee classified caffeine as a supplement with strong evidence to support its ergogenic effect (2). Caffeine appears to have ergogenic effects on a variety of exercise performance outcomes, including aerobic and muscular endurance, muscular strength, power, and jumping performance (3–5). Recommendations for caffeine supplementation generally include ingesting doses from 3 to 6 mg/kg around 30 to 60 min before exercise (3–5). While the exact mechanisms underpinning caffeine's effects are not fully understood, it is believed that caffeine enhances performance by binding to adenosine receptors, reducing perceived exertion, and improving muscle contractile properties (4–6). Caffeine is a legal supplement, even though, some organizations such as the NCAA, limit caffeine urine concentrations to 15 µg/mL.

One major limitation of the current body of evidence is the high prevalence of male participants in studies (3, 7). A recent bibliographic analysis highlighted this issue by finding that only 13% of participants in 362 studies on caffeine and exercise included females (7). The same issue was reinforced by an umbrella review which observed that males accounted for 72% to 100% of the pooled number of participants in 21 meta-analyses on caffeine and exercise performance (3). For example, a 2018 meta-analysis explored caffeine's effects on vertical jump performance (8). While an overall ergogenic effect was observed, only 14% of the included participants were females. The authors conducted a subgroup analysis to explore the effects of caffeine on jumping performance in females, but the pooled effect size was not significant, with a wide 95% confidence interval (CI) (Hedges' g: 0.23; 95% CI: −0.23, 0.69), likely because only two studies were included (9, 10). Therefore, a strong argument can be made that the generalizability of findings in previous meta-analyses to female participants is limited.

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In recent years, several studies explored caffeine's effects on vertical jumping performance in females (9–23). This topic appears to be gaining in popularity as only in 2021 and 2022 there have been six studies on the topic (11–13, 16, 21, 22). However, while there is an increase in the evidence base, the findings between studies remain conflicting. For example, some studies reported an ergogenic effect, while others suggest that caffeine may not enhance vertical jumping performance in females (9, 10, 15, 19). The variation in between-study findings could be due to several reasons, such as the phase of the menstrual cycle at which the data was collected. Caffeine metabolism may vary according to the phase of the menstrual cycle, which might also impact caffeine's ergogenic effects (24). Other factors, such as testing time of day and caffeine dose, may also explain some of the divergent findings. For example, there is evidence to suggest a preferential ergogenic effect of caffeine in the morning vs. evening (25). Caffeine dose may also impact its ergogenic effect, as a low dose (e.g., 2 mg/kg) may not yield similar effects as higher doses (10, 11). Studies on the topic have varied in their methodological approach (e.g., testing at different phases of the menstrual cycle or times of day), and currently, the influence of these moderator variables on jumping performance in females has yet to be thoroughly examined (9–23).

Vertical jump performance assessment are commonly used to evaluate the efficacy of a given exercise intervention (e.g., plyometric training) (26). Additionally, improvements in vertical jump height may directly impact sport-specific outcomes (e.g., rebound in basketball) (27). The importance of vertical jump performance for both practical assessments and sport-specific situations highlights the requirement to determine the efficacy of a nutritional supplement, such as caffeine, on this outcome. Due to these factors, and given some of the outlined limitations in the existing literature, we aimed to perform a systematic review and meta-analysis of caffeine's overall effects on vertical jumping performance in females, with additional analyses for potential moderator variables.

Methods

Search strategy

We searched through five databases to identify studies that examined the effects of caffeine on jumping performance in females. Three databases that index published articles were searched, namely, PubMed/MEDLINE, Scopus, and Web of Science. We also searched through the Networked Digital Library of Theses and Dissertations and Open Access Theses and Dissertations, which are databases that index unpublished documents in the form of theses and dissertations. In all databases, the following search syntax was used: (caffeine OR coffee) AND (jump OR jumping OR "countermovement jump" OR "counter movement jump" OR "squat jump" OR plyometrics OR "sargent test" OR "jump height" OR "vertical jump"). Quotation marks were used for phrase searching. The search in the databases was performed on October 12th, 2022, and was done independently by two authors of the review (JG and DV). Following the search across the databases, a secondary search was performed, which included examining the references of previous related meta-analyses (8, 28–30) for any potential articles that were not found in the primary search.

Inclusion criteria

Using the PICO model, we included studies that satisfied the following criteria: P (population)—females; I (intervention)—caffeine supplementation provided pre-exercise; C (comparison)—placebo; O (outcome)—vertical jump height. Besides these criteria, studies were also required to be written in English and used a double-blind or triple-blind crossover design.

Data extraction

Two authors of the review (JG and DV) independently performed data extraction from the included studies for the following variables: (a) lead author's last name and year of publication; (b) characteristics of the included participants (e.g., age, training status, sample size); (c) caffeine supplementation protocol; (d) methodological aspects of the study such as the phase of the menstrual cycle at which the data collection was performed, testing time of day, type of jump test; and (e) performance values recorded during the placebo and caffeine trials.

Risk of bias

The risk of bias among the included studies was examined using the RoB 2 checklist, which includes additional considerations for crossover study designs (31). This checklist evaluates the risk of bias that may occur due to the following aspects: randomization process (domain 1); period and carryover effect (domain S); deviations from intended intervention (domain 2); missing data (domain 3); measurement of the outcome (domain 4); selection of the reported result (domain 5). Each of these domains and the summary risk of bias are classified as "low risk", "some concerns", or "high risk". Evaluations were performed independently by two authors of the review (JG and DV), with discussions and eventual consensus for differences in assessments.

Quality of evidence

The quality of evidence was evaluated at the meta-analysis level, using the Grading of Recommendations, Assessment, Development and Evaluations (GRADE) assessment (32). In the GRADE assessment, the quality of evidence is downgraded based on the risk of bias, inconsistency, indirectness, imprecision, and publication bias. Evidence is downgraded by one or two levels. The quality of evidence is upgraded based on the presence of a large effect, dose-response relationship, and the effect of plausible residual confounding. Evidence is upgraded by up to two levels for the presence of a large

effect size or by one level for a dose-response relationship and the effect of plausible residual confounding. The overall quality of evidence was classified as "high quality", "moderate quality", "low quality", or "very low quality".

Statistical analysis

Meta-analyses were performed based on standardized mean differences with small sample bias corrections (Hedges' g). Hedges' g effect sizes were calculated as the difference in means (caffeine – placebo) divided by their pooled standard deviation. Calculation of Hedges' g is based on the caffeine and placebo performance data (mean ± standard deviation), the total sample size, and the correlation between the trials. As the studies did not present correlation between the trials, correlation was calculated using the individual participant data provided in one study (16). Correlation values in this study amounted to $r = 0.95$, which was the value subsequently used for all other studies. Several studies reported multiple outcomes that were obtained from the same group of participants (e.g., jump performance in two different tests). For these studies, we first calculated effect sizes and variances for each outcome, and then used the average values in the meta-analysis. In the main meta-analysis, we pooled the data from all included studies. Subgroup analyses were performed for the phase of the menstrual cycle (luteal phase, follicular phase, luteal or follicular, phase not specified), testing time of day (morning, evening, mixed morning or evening, time not specified), caffeine dose (≤3 mg/kg or >3 mg/kg), and test type (squat jump [SJ] and countermovement jump [CMJ]) as possible moderators of caffeine's effects. The utilized classification for caffeine dose was based on the consideration that doses of ≤3 mg/kg are generally associated with minimal side effects (e.g., insomnia, jitters, nausea), whereas these side effects linearly increase with caffeine doses >3 mg/kg (33). Hedges' g effect sizes are presented with their respective 95% CIs and were interpreted as: trivial (<0.20), small (0.20–0.49), medium (0.50–0.79), and large (≥0.80) (34). I^2 was calculated to evaluate heterogeneity and was interpreted as low (≤50%), moderate (50–75%), and high (>75%) levels of heterogeneity. The presence of publication bias was evaluated by examining the asymmetry of the funnel plot. Evaluation of publication bias was performed only in the main meta-analysis, given that other subgroup analyses were generally limited by the inclusion of fewer than ten studies (35). The statistical significance was tested at $p < 0.05$. All analyses were performed using the Comprehensive Meta-Analysis software, version 2 (Biostat Inc., Englewood, NJ, USA).

Results

Search results

In the primary search that involved examining the search results in the five databases, there were 560 references. We excluded 535 references after reading their titles or abstracts. As a result, 25 full-text papers were read. Fourteen studies were found to satisfy the inclusion criteria (9, 11–23). In the secondary search that involved examining references of previous related reviews, there were 209 results, and one additional study (10) was identified. Therefore, 15 studies were included in the review (9–23) (Figure 1).

Summary of the included studies

The sample sizes among the included studies ranged from 8 to 18 participants (pooled $n = 197$). Ten studies included athletes participating in various individual or team sports, such as basketball, handball, soccer, volleyball, karate, hockey, netball, weightlifting, or Jiu-Jitsu (Table 1). Four studies included resistance-trained females, while one included participants classified as recreationally active. Fourteen studies provided caffeine doses ranging from 2 to 6 mg/kg. One study provided caffeine in an absolute dose of 200 mg (~3.2 mg/kg). Caffeine was most commonly provided 60 min before exercise (Table 1). Fourteen studies evaluated CMJ performance, while five studies evaluated SJ performance. Four studies did not report the time of day the testing was conducted. Six studies tested performance in the evening, while four evaluated performance in the morning. Two studies reported that the testing time of day was either in the morning or evening, depending on the participants' preference. Seven studies did not specify at which phase of the menstrual cycle the testing was conducted. Three studies collected the performance data either in the luteal or follicular phase (depending on each participant). The testing was performed during the follicular phase in three studies. Three studies evaluated performance during the luteal phase. Of note, several studies reported on several related outcomes. For example, five studies evaluated both CMJ and SJ performance, and two studies evaluated performance of all participants both in the morning and evening hours on separate days.

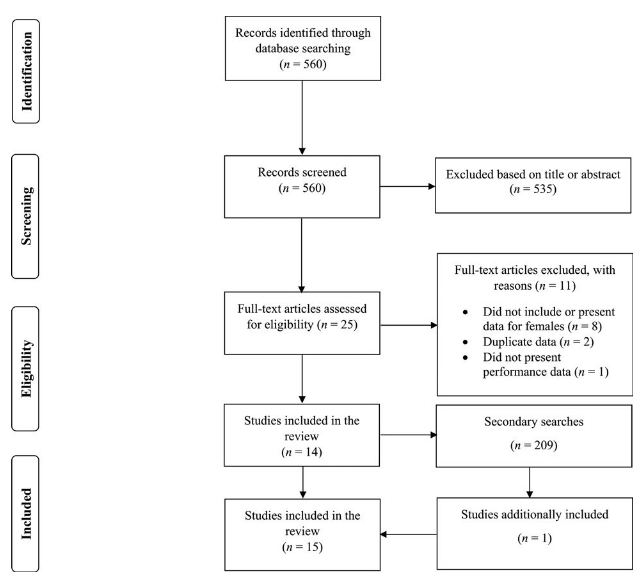

Figure 1. Flow diagram of the search process.

Table 1. Summary of the studies included in the review.

Reference	Participants	Caffeine protocol	Jump test	Testing time of day	Phase of the menstrual cycle	Study findings
Ali et al. (9)	10 female team sports athletes (soccer, hockey and netball)	6 mg/kg in capsule ingested 60 min before exercise	CMJ	Not specified	Not specified	↔ between conditions
Arazi et al. (10)	10 teenage female karate athletes	2 or 5 mg/kg in capsule ingested 60 min before exercise	CMJ (Sargent test)	Morning	Not specified	↔ between conditions
Bougrine et al. (11)	15 young female handball players	6 mg/kg in capsule ingested 60 min before exercise	SJ	Morning (08:00 h) and evening (18:00 h)	Luteal or follicular phase	↑ in SJ height following caffeine ingestion in the morning and evening, with greater effects found in the morning
Burke et al. (12)	11 female collegiate volleyball players or weightlifters	6 mg/kg in capsule ingested 60 min before exercise	CMJ and SJ	Morning	Not specified	↑ in CMJ and SJ height following caffeine ingestion
Filip-Stachnik et al. (13)	14 female volleyball players	6 mg/kg in capsule ingested 60 min before exercise	CMJ	Evening (17:00 to 19:00 h)	Not specified	↔ between conditions
Harty et al. (14)	11 resistance-trained females	6 mg/kg in liquid ingested 30, 60, or 120 min before exercise	CMJ	Not specified	Follicular phase	↑ in CMJ height following caffeine ingestion at all three time points
Lara et al. (15)	18 female soccer players	3 mg/kg in an energy drink ingested 60 min before exercise[a]	CMJ	Evening (19:00 h)	Not specified	↑ in CMJ height following caffeine ingestion
Merino Fernández et al. (16)	8 female Jiu-Jitsu athletes	3 mg/kg in capsule ingested 60 min before exercise	CMJ	Not specified	Not specified	↑ in CMJ height following caffeine ingestion
Montgomery (17)	18 recreationally active females	200 mg in caffeine chewing gum consumed 10 min before exercise	CMJ and SJ	Morning or evening (individualized for each participant)	Not specified	↑ in SJ height following caffeine ingestion ↔ between conditions for CMJ height
Muñoz et al. (18)	15 female handball players	3 mg/kg in capsule ingested 60 min before exercise	CMJ	Evening (18:00 h)	Luteal (5 participants) or follicular (10 participants) phase	↑ in CMJ height following caffeine ingestion
Norum et al. (19)	15 resistance-trained females	4 mg/kg in capsule ingested 60 min before exercise	CMJ	Morning or evening (individualized for each participant)	Follicular phase	↑ in CMJ height following caffeine ingestion
Pérez-López et al. (20)	13 young female volleyball players	3 mg/kg in an energy drink ingested 60 min before exercise[a]	CMJ and SJ	Evening	Luteal (9 participants) or follicular (4 participants) phase	↑ in CMJ and SJ height following caffeine ingestion
Robles-González et al. (21)	15 resistance-trained females	3 mg/kg in liquid ingested 30 min before exercise	CMJ	Morning (09:00 to 11:00 h) and evening (17:00 to 19:00 h)	Luteal phase	↑ in CMJ height following caffeine ingestion in the morning and evening
Santana et al. (22)	14 resistance-trained females	5 mg/kg in capsule ingested 60 min before exercise	CMJ	Not specified	Luteal (all participants) or follicular (all participants) phase	↑ in CMJ height following caffeine ingestion in the luteal and follicular phase, with greater effects found in the luteal phase
Stojanović et al. (23)	10 female basketball players	3 mg/kg in capsule ingested 60 min before exercise	CMJ and SJ	Evening (19:00 to 21:00 h)	Luteal phase	↔ between conditions

[a]the only difference between the energy drink and placebo conditions was the amount of caffeine consumed, allowing the isolation of caffeine's effect; CMJ: countermovement jump; SJ: squat jump; ↔: no significant difference; ↑: significant increase.

Risk of bias

In domain 1 and domain 5 of the RoB 2 checklist, all studies scored "some concerns". In all other domains, studies scored "low risk". The overall evaluation of the risk of bias for all included studies was "some concerns".

Meta-analysis results

Overall analysis

In the main meta-analysis, we found an ergogenic effect of caffeine on vertical jumping performance (Hedges' g: 0.28; 95% CI: 0.21, 0.34; I^2 = 26%; $p < 0.001$; Figure 2). We did not detect funnel plot asymmetry.

Subgroup analysis according to menstrual cycle phase

An ergogenic effect of caffeine on vertical jumping performance was found when the testing was carried out in the luteal phase (Hedges' g: 0.24; 95% CI: 0.09, 0.40; I^2 = 20%; $p = 0.002$; Table 2), follicular phase (Hedges' g: 0.52; 95% CI: 0.37, 0.67; I^2 = 0%; $p < 0.001$), luteal or follicular phase (Hedges' g: 0.31; 95% CI: 0.18, 0.43; I^2 = 0%; $p = 0.005$), and when the phase was not specified (Hedges' g: 0.21; 95% CI: 0.13, 0.29; I^2 = 0%; $p < 0.001$). The test for subgroup

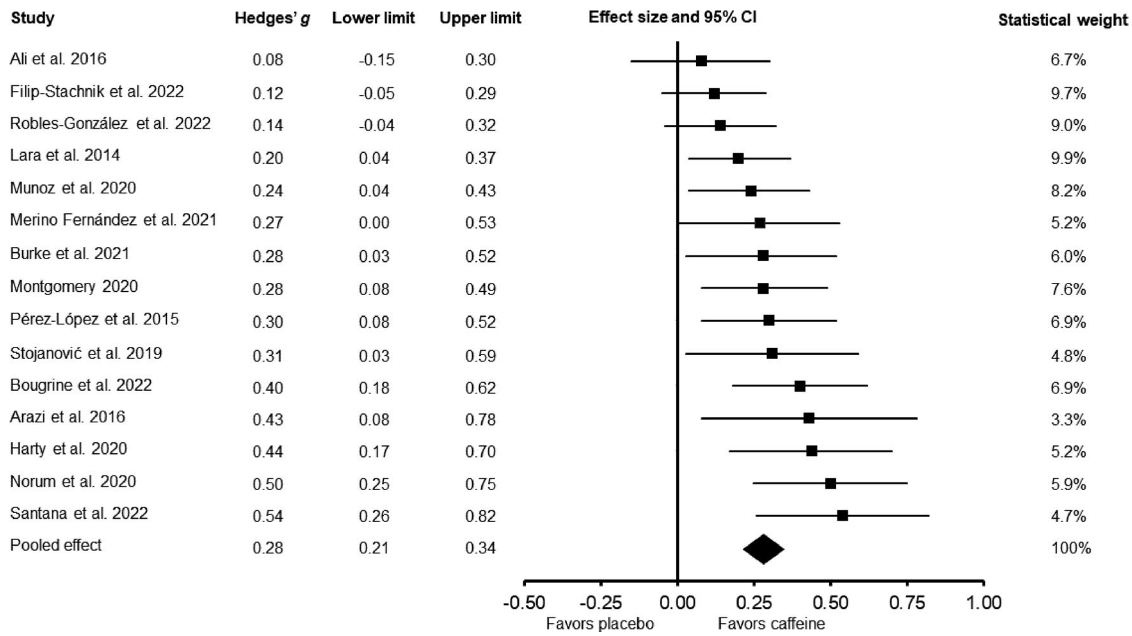

Figure 2. Forest plot presenting the difference between caffeine and placebo for jump height in females. The squares represent effect size (Hedges' *g*), while the whiskers are their 95% confidence intervals (CI). The diamond at the bottom represents the pooled effect size. Studies are ordered from lowest to largest effect size.

Table 2. Results from the subgroup meta-analyses.

Subgroup analysis	Classification	Included studies*	Pooled effect (*g* and 95% CI)	Subgroup differences
Menstrual cycle phase	Luteal phase	[21, 22, 23]	0.24 (0.09, 0.40)	Follicular phase vs. luteal phase ($p = 0.01$) vs. luteal or follicular ($p < 0.001$) and vs. when phase was not specified ($p = 0.03$).
	Follicular phase	[14, 19, 22]	0.52 (0.37, 0.67)	
	Luteal or follicular phase	[11, 18, 20]	0.31 (0.18, 0.43)	
	Phase not specified	[9, 10, 12, 13, 15, 16, 17]	0.21 (0.13, 0.29)	
Testing time of day	Morning	[10, 11, 12, 21]	0.38 (0.13, 0.63)	Test was not significant ($p = 0.16$)
	Evening	[11, 13, 15, 18, 20, 21, 23]	0.19 (0.11, 0.26)	
	Mixed morning and evening	[17, 19]	0.38 (0.17, 0.59)	
	Time not specified	[9, 14, 16, 22]	0.32 (0.11, 0.53)	
Caffeine dose	≤3 mg/kg	[10, 15, 16, 18, 20, 21, 23]	0.21 (0.13, 0.30)	Test was not significant ($p = 0.07$)
	>3 mg/kg	[9, 10, 11, 12, 13, 14, 17, 19, 22]	0.37 (0.22, 0.52)	
Test type	CMJ	[9, 10, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23]	0.26 (0.19, 0.33)	Test was not significant ($p = 0.12$)
	SJ	[11, 12, 17, 20, 23]	0.35 (0.25, 0.46)	

*Some studies included multiple trials and are included in different categories within a given subgroup analysis; *g*: Hedges' *g*; CI: confidence interval; CMJ: countermovement jump test; SJ: squat jump.

differences indicated that the ergogenic effects of caffeine were significantly greater in the follicular phase when compared either to luteal ($p = 0.01$), luteal or follicular ($p < 0.001$) or when the phase was not specified ($p = 0.03$).

Subgroup analysis according to testing time of day

An ergogenic effect of caffeine on vertical jumping performance was found when the testing was carried out in the morning (Hedges' *g*: 0.38; 95% CI: 0.13, 0.63; I^2 = 77%; $p = 0.003$), evening (Hedges' *g*: 0.19; 95% CI: 0.11, 0.26; I^2 = 0%; $p < 0.001$), mixed morning or evening (Hedges' *g*: 0.38; 95% CI: 0.17, 0.59; I^2 = 41%; $p < 0.001$), and when time was not specified (Hedges' *g*: 0.32; 95% CI: 0.11, 0.53; I^2 = 60%; $p = 0.002$). The test for subgroup differences was not significant ($p = 0.16$).

Subgroup analysis according to caffeine dose

An ergogenic effect of caffeine on vertical jumping performance was found when the dose was ≤3 mg/kg (Hedges' *g*: 0.21; 95% CI: 0.13, 0.30; I^2 = 0%; $p < 0.001$), or >3 mg/kg (Hedges' *g*: 0.37; 95% CI: 0.22, 0.52; I^2 = 70%; $p < 0.001$). The test for subgroup differences was not significant ($p = 0.07$).

Subgroup analysis according to test type

An ergogenic effect of caffeine on vertical jumping performance was found in the CMJ test (Hedges' *g*: 0.26; 95% CI: 0.19, 0.33; I^2 = 26%; $p < 0.001$) and SJ test (Hedges' *g*: 0.35; 95% CI: 0.25, 0.46; I^2 = 0%; $p < 0.001$). The test for subgroup differences was not significant ($p = 0.12$).

Table 3. Results of grading of recommendations assessment, development and evaluation (GRADE) assessment.

	Items for downgrading quality of evidence					Items for upgrading the quality of evidence			
Analysis	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	Large effect	Dose-response	Confounding	Overall quality of evidence*
Main meta-analysis	↓	↔	↔	↔	↔	↔	↔	↑	⊕⊕⊕⊕
Luteal phase	↓	↔	↔	↓	↔	↔	↔	↑	⊕⊕⊕O
Follicular phase	↓	↔	↔	↓	↔	↔	↔	↑	⊕⊕⊕O
Luteal or follicular phase	↓	↔	↔	↓	↔	↔	↔	↑	⊕⊕⊕O
Phase not specified	↓	↔	↔	↓	↔	↔	↔	↑	⊕⊕⊕O
Testing in the morning	↓	↓	↔	↓	↔	↔	↔	↑	⊕⊕OO
Testing in the evening	↓	↔	↔	↓	↔	↔	↔	↑	⊕⊕⊕O
Mixed morning or evening	↓	↔	↓	↓	↔	↔	↔	↑	⊕⊕OO
Testing time not specified	↓	↔	↔	↓	↔	↔	↔	↑	⊕⊕⊕O
Caffeine dose ≤3 mg/kg	↓	↔	↔	↓	↔	↔	↔	↑	⊕⊕⊕O
Caffeine dose >3 mg/kg	↓	↓	↔	↓	↔	↔	↔	↑	⊕⊕OO
SJ	↓	↔	↔	↔	↔	↔	↔	↑	⊕⊕⊕⊕
CMJ	↓	↔	↔	↓	↔	↔	↔	↑	⊕⊕⊕O

⊕⊕⊕⊕ = high quality; ⊕⊕⊕O = moderate quality; ⊕⊕OO = low quality; ↓ quality of evidence downgraded for one level; ↔ no downgrade or upgrade; ↑ upgraded by one level; CMJ: countermovement jump; SJ: squat jump.

GRADE assessment

Out of the performed meta-analyses, the majority (8/13) were classified as having moderate quality evidence (Table 3). Two analyses were classified as high quality (overall meta-analysis and analysis for SJ). Three analyses were classified as low quality (testing in the morning, mixed morning or evening, and caffeine dose >3 mg/kg). Most commonly, analyses were downgraded for the quality of evidence on the risk of bias and imprecision items. The quality of evidence was upgraded on the item for the effects of plausible residual confounding.

Discussion

Main findings

The present systematic review is the first to synthesize the evidence on the effects of caffeine on vertical jumping performance in females, which also explored the influence of possible moderators such as the phase of the menstrual cycle, testing time of day, caffeine dose, and type of jump test. Our main findings are: (1) caffeine ingestion is ergogenic for vertical jumping performance in females; (2) the largest ergogenic effects of caffeine on jumping performance are observed in the follicular phase of the menstrual cycle; (3) the magnitude of caffeine's effects may not depend on the testing time of day; (4) both low and high caffeine doses appear to be comparably ergogenic; and (5) similar ergogenic effects are likely expected for SJ and CMJ tests.

Overall effects of caffeine

In the primary meta-analysis, we found that caffeine ingestion is ergogenic for vertical jumping performance in females. The magnitude of these effects (Hedges' *g*: 0.28) is similar to previous meta-analyses that focused on vertical jumping performance (Hedges' *g*: 0.17 to 0.29) (8, 28–30). However, several limitations observed in previous meta-analyses should be considered. For example, two meta-analyses reported an ergogenic effect of caffeine on jumping performance, but only 14% and 6% of the participants included in the meta-analyses were females, respectively (8, 28). A recent meta-analysis (30) focused only on female participants, and while an ergogenic effect on jumping performance was observed, only six studies were included. Some of the included studies (36) also evaluated the effects of a multi-ingredient energy drink on performance, and therefore, the effects of caffeine cannot necessarily be isolated. The previous review also only focused on team-sport female athletes and did not perform any additional moderator analyses, likely owing to the low number of included studies. In summary, here we provided the most comprehensive review of caffeine's effects on jumping performance in females. In a meta-analysis including ~200 participants, we found a small but very precise ergogenic effect of caffeine on vertical jumping performance (Hedges' *g*: 0.28; 95% CI: 0.21, 0.34). The high quality of evidence observed in this meta-analysis further reinforces the strength of these findings.

Effects of caffeine according to menstrual cycle phase

The menstrual cycle is broadly divided into three phases: (1) the follicular phase; (2) the ovulatory phase; and (3) the luteal phase (37). According to previous data, caffeine's systemic clearance may differ between the follicular and luteal phases, with the luteal phase exhibiting slower caffeine elimination (24). Therefore, menstrual cycle phase has been suggested as a possible moderator of caffeine's effects on exercise performance (22). Indeed, our meta-analysis found that caffeine's ergogenic effect on vertical jumping performance was the largest in the follicular phase (Hedges' *g*: 0.52 vs. 0.21-0.31). A recent meta-analysis evaluated exercise performance during all phases of the menstrual cycle (37). This analysis found that exercise performance is attenuated during the follicular phase compared to all other phases (37). The follicular phase-induced reduction in exercise performance is associated with several physiological effects, among which is a reduction in voluntary activation (38). Evidence indicates that caffeine ingestion increases voluntary activation, which may contribute to caffeine's ergogenic effects (39). For example, improvements in isometric,

concentric, and eccentric muscular strength following caffeine supplementation were associated with increased voluntary activation (40). Thus, as performance is attenuated in the follicular phase, consuming a stimulant such as caffeine may produce larger effects compared to other phases (e.g., luteal), during which performance is at baseline levels. In summary, while an ergogenic effect of caffeine on vertical jumping performance may be expected in the follicular and luteal phases, we provide evidence that the effects are greater in the follicular phase.

Effects of caffeine according to testing time of day

Testing time of day has been suggested as an important methodological factor when evaluating caffeine's effects on exercise performance (25). Studies have observed that exercise performance for most outcomes—including jump height—tends to peak in the evening (41–43). Exercise performance peaks in the evening, likely because this time of day coincides with peak core body temperature, facilitating actin-myosin cross-bridging in skeletal muscle (44, 45). As exercise performance is already at a higher level in the evening hours, it is proposed that caffeine's ergogenic effects are greater in the morning and may not even occur in the evening (25). Our analysis indicates that caffeine ingestion elicits an ergogenic effect when consumed in the morning and evening. While the pooled effect size favored the morning (Hedges' g: 0.38 vs. 0.19), the test for subgroup differences was not significant. A limitation of this analysis is that only four studies (10–12, 21) evaluated performance in the morning hours. Two of these studies also incorporated an evening testing session (11, 21). Both studies reported an ergogenic effect in the evening and morning, even though the magnitude of the effect was greater in the morning (3-4% vs. 1-1.5%). In summary, we found that the ergogenic effect of caffeine on vertical jumping performance occurs in the morning and evening. While our test for subgroup differences was not significant, more studies are needed to directly compare the effects of caffeine on jumping performance in females in the morning vs. evening.

Effects of caffeine according to caffeine dose

When categorizing studies according to caffeine dose, an ergogenic effect on vertical jumping performance was observed with caffeine doses ≤3 mg/kg and >3 mg/kg. While we found an ergogenic effect of caffeine doses ≤3 mg/kg, it remains unclear what the minimal effective caffeine dose is. Specifically, only one study (10) utilized a caffeine dose lower than 3 mg/kg. This study provided 2 mg/kg of caffeine and reported that jumping performance was identical (mean of 29 cm) following the ingestion of this dose compared to placebo (10). One dose-response study compared the effects of caffeine doses of 2, 4, and 6 mg/kg on vertical jump performance and observed that all three doses were comparably ergogenic (46). However, this study was conducted with a sample of male participants. Therefore, future dose-response studies using even lower doses are needed to establish the minimal ergogenic caffeine dose on vertical jumping performance in females.

Effects of caffeine according to test type

The SJ and CMJ are tests commonly used to evaluate vertical jumping performance. In most cases, jump height is greater in the CMJ test due to factors such as: (a) greater uptake of muscle slack; and (b) the build-up of stimulation during the countermovement (47). As these tests have different physiological effects, we also performed moderator analysis for caffeine's performance-enhancing effects according to test type. When examining these two tests from a caffeine supplementation standpoint, our results indicate that caffeine ingestion is ergogenic for jump height in the SJ and CMJ. Based on our findings, caffeine supplementation may be considered for increasing SJ and CMJ height in females.

Risk of bias and quality of evidence

Studies were rated as having some concerns regarding the risk of bias. These evaluations were provided, given that the studies did not report on allocation concealment and were also not pre-registered. Future studies should therefore consider pre-registration and reporting on allocation concealment. On the GRADE checklist, we downgraded the quality of evidence because of the increased risk of bias, as indicated on the RoB 2 scale (32). Analyses were also downgraded for quality of evidence because of inconsistency, as they had a high I^2 and no between-study overlap in the 95% CI of effect sizes (32). Another reason for downgrading was imprecision, as some pooled effects had wide 95% CIs, which overlapped between the thresholds for different effect sizes (32). Despite these evaluations, most analyses were rated as providing moderate quality evidence, which increases our confidence in the conclusions presented herein.

Limitations and future directions

For some subgroup analyses (Table 2), there were only a few included studies, highlighting the need for future studies directly exploring the influence of these moderators. Another limitation of this review is that we only focused on vertical jump performance. The vast majority of studies that explored the effects of caffeine on jumping performance utilized different variations of vertical jumps (8, 28–30). A recent study investigated the effects of caffeine on long jump performance and did not observe an ergogenic effect (48). This study, however, included both males and females but did not explore if there are possible sex-specific effects. Therefore, future studies examining the effects of caffeine on different variations of horizontal jump performance in both sexes are needed.

Vertical jumps performed on a force platform allow for the opportunity to analyze a multitude of variables, such as rate of force development, impulse, power, force, velocity,

and others (49). However, 73% of the included studies only analyzed caffeine's effect on jump height. Therefore, the effects on other jumping-related variables remain largely undetermined. Only one included study provided a detailed assessment of caffeine's effect on these variables and reported an ergogenic effect on flight time, flight time:contraction time, concentric impulse, peak power, eccentric mean braking force, and reactive strength index (16). Future studies on this topic should also consider reporting and analyzing other jumping performance variables, not only jump height.

The included studies also differed in their method of calculating jump height. Specifically, some studies estimated jump height using flight time, while others used take-off velocity (16, 19). More importantly, the specific calculation method was not even reported in most included studies, which is another limitation. Even though the utilized method was likely standardized within-study (i.e., the same procedure was used both in the caffeine and placebo trial), thus allowing the isolation of the treatment effect, future studies should ensure that they report their used method and force plate sampling frequency to allow for a more informed comparison of results between studies. Finally, there are other avenues of research on this topic that future studies may consider, such as the influence of caffeine mode of administration, habituation, and genotype effects, among others (for a review on the topic, see (50)).

Conclusions

We performed a comprehensive review of the overall and moderator effects of caffeine on vertical jumping performance in females. In the main meta-analysis, which included 15 studies and ~200 participants, we found a small but very precise ergogenic effect of caffeine on jumping performance. Moderator analyses indicated that caffeine's effects on vertical jumping performance are influenced by the menstrual cycle phase. While a performance improvement was found in all analyses, the ergogenic effects were the largest in the follicular phase. An ergogenic effect of caffeine was consistently found in analyses for the testing time of day (morning, evening, mixed morning, or evening, or not specified), caffeine dose (≤3 mg/kg or >3 mg/kg), and test type (SJ or CMJ), and there were no significant subgroup differences. In summary, caffeine ingestion is ergogenic for vertical jumping performance in females, and it seems that these effects are the largest in the follicular phase of the menstrual cycle.

Disclosure statement

No potential conflict of interest was reported by the authors.

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