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REVIEW

Acute effects of caffeine-containing energy drinks on physical performance: a systematic review and meta-analysis

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Abstract

Purpose Caffeine-containing energy drinks (EDs) are currently used as ergogenic aids to improve physical performance in a wide variety of sport disciplines. However, the outcomes of previous investigations on this topic are inconclusive due to methodological differences, especially, in the dosage of the active ingredients and the test used to assess performance.

Methods We performed a systematic review and meta-analysis of published studies to evaluate the effects of acute ED intake on physical performance. The search for references was conducted in the databases PubMed, ISI Web of Knowledge and SPORTDiscus until December 2015.

Results Thirty-four studies published between 1998 and 2015 were included in the analysis. Using a random-effects model, effect sizes (ES) were calculated as the standardized mean difference. Overall, ED ingestion improved physical performance in muscle strength and endurance (ES = 0.49; $p < 0.001$), endurance exercise tests (ES = 0.53; $p < 0.001$), jumping (ES = 0.29; $p = 0.01$) and sport-specific actions (ES = 0.51; $p < 0.001$), but not in sprinting (ES = 0.14; $p = 0.06$). The meta-regression demonstrated a significant association between taurine dosage (mg) and performance (slope = 0.0001; $p = 0.04$), but not between caffeine dosage (mg) and performance (slope = 0.0009; $p = 0.21$).

Conclusion ED ingestion improved performance in muscle strength and endurance, endurance exercise tests, jumping and sport-specific actions. However, the improvement in performance was associated with taurine dosage.

Keywords Caffeine · Taurine · Performance-enhancing substances · Sports

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Introduction

Caffeine is a central nervous stimulant, acting through the blockade of central and peripheral adenosine receptors [1]. As a result of this stimulant action, caffeine ingestion produces greater recruitment of motor units [2], the mobilization of free fatty acids [3] and mobilization of calcium in the sarcoplasmic reticulum [4]. Therefore, caffeine is often used as an ergogenic aid to improve performance both before [5, 6] and during exercise [7]. Currently, one of the most common and simple ways to consume caffeine is through the intake of caffeine-containing energy drinks (ED) [8]. As well as caffeine, EDs usually contain other substances that promote synergistic or additive effects in addition to the action of the caffeine, such as vitamins, minerals, carbohydrates, amino acids and taurine [9].

ED consumption may be associated with different objectives, such as increasing attention, mental alertness and

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metabolism [10]. Besides these objectives, it has been suggested that ED acts on physical performance [11]. Thus, several studies have been conducted in recent years to analyze the effects of ED consumption on different types of performance, such as sports [12–15], strength training [16], sprints [17], jumps [18] and aerobic activities [19, 20]. Although some studies have indicated a positive effect of ED on performance [15, 21], other studies have not observed this relationship [22, 23]. The differences between these results may be related to the different types of exercises, dosage and ED compositions used.

Although some review studies have suggested that EDs increase performance [8, 9], further studies are needed to reach a definitive conclusion on the subject. In this context, a systematic literature review identifies studies in different databases, and by means of defined inclusion criteria, selects studies associated with the theme. In addition, meta-analysis allows integrated analysis of the results of these studies, identifying potential moderating variables that could influence performance.

To our knowledge, to date, there are no systematic literature reviews with meta-analysis on the intake of EDs and their effectiveness to increase physical performance. Thus, the objective of this study was to conduct a systematic review of the literature with regard to the effects of pre-exercise ED intake on physical performance and subsequently apply a meta-analysis to identify variables that could influence physical performance.

Materials and methods

Search strategy and study selection

The search for references was conducted in the databases PubMed, ISI Web of Knowledge and SPORTDiscus up to December 31st 2015. Search terms included a mix of Medical Subject Headings (MeSH terms) and free-text words for key concepts related to exercise and the ED ingredients. When possible, these were combined with a sensitive search strategy to identify trials performed in "humans". The full search criteria for the PubMed database were: ("energy drinks" [mesh] OR "energy drinks" OR "energy drink" OR beverages [mesh] OR beverages OR beverage) AND (caffeine [mesh] OR caffeine OR "1,3,7 trimethylxanthine" OR "1,3,7-trimethylxanthine") AND ("athletic performance"[mesh] OR "athletic performance" OR "athletic performances" OR "sport performance" OR "sports performances" OR sports[mesh] OR sports OR sport OR athletic OR athletics OR exercise[mesh] OR exercises OR "physical exercise" OR physical exercises OR "isometric exercises" OR "isometric exercise" OR "aerobic exercises" OR "aerobic exercise" OR "plyometric exercise" OR "plyometric training" OR "circuit-based exercise" OR "resistance training" OR "resistance exercise" OR "resistance exercises" OR "endurance training" OR "endurance exercise" OR "endurance exercises" OR running OR walking OR sprint OR sprints OR "repeated sprints" OR "jump training" OR "jump exercise" OR "jump exercises" OR "strength training" OR "strength exercise" OR "strength exercises" OR "physical conditioning" OR "concurrent training").

The following were disregarded: (1) case reports; (2) review articles; (3) the use of drugs/substances which influenced the outcome; (4) caffeine use without ED; (5) ED use without caffeine; (6) subjects on energy-restricted diets and/or weight reduction programs; (7) articles with animal models; (8) studies with samples that were ill or had physical limitations for exertion; (9) longitudinal studies. The following were considered for the analysis: (1) original articles; (2) articles with healthy humans; (3) adults (over 18 years); (4) articles that reported the caffeine dose in the ED; (5) measures of physical performance pre- and post-intervention; (6) a placebo group/session; (7) availability of data for effect size calculation and (8) studies with an acute intervention.

Studies included in the review

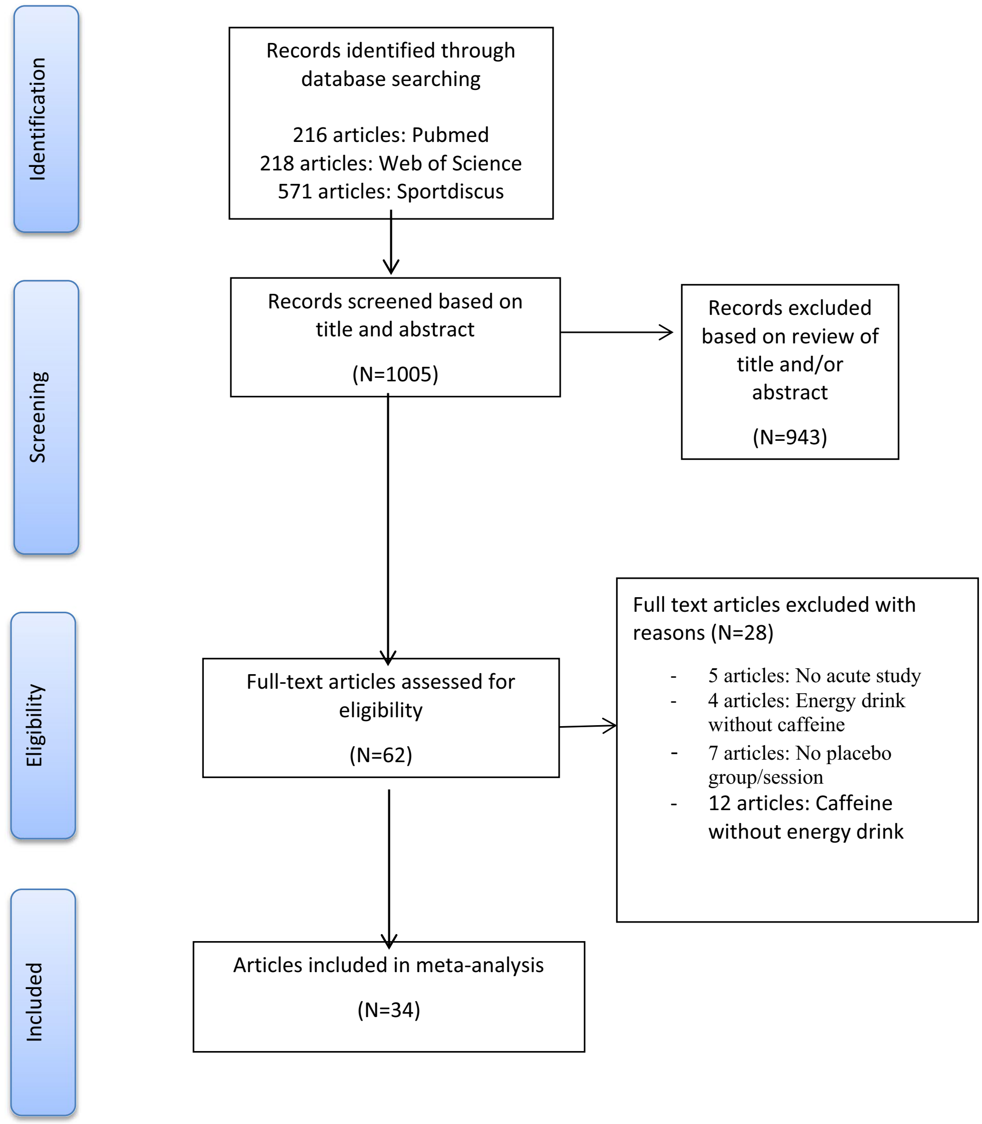
The search in the databases provided 1005 articles. Of the articles found, 943 were excluded after reading the title and abstract, resulting in 62 articles of which the full text was read. Of these, 28 were excluded as they did not meet at least one of the inclusion criteria. Thus, 34 studies were considered in the final analysis (Fig. 1).

Data extraction and quality assessment

Data on study source, study design, study quality, journal impact factor, sample size, characteristics of the participants, ED ingredients (specifically the amounts caffeine and taurine) and outcomes of the interventions were extracted independently by two authors (DS and JC) using a specifically developed electronic data extraction sheet. Using the Cohen's kappa coefficient, the overall agreement rate between the two extractors of information, prior to correcting discrepant items, was 0.92. Subsequently, disagreements were resolved through discussion. A priori, the main outcomes were changes in measures of physical performance induced by the ingestion of EDs. Changes in performance were subdivided into endurance exercise tests (cycle ergometer, running/treadmill), sprinting (cycle ergometer, running), muscle strength and endurance (dynamic, concentric, isometric), jumping and sport-specific actions (cycling, running, jumping).

Study quality was assessed using the PEDro Scale which has been reported to be valid [24] and reliable [25]. All assessments were conducted in duplicate, independent of

Fig. 1 Flowchart of studies included in the review



each other. Disagreements were resolved through consensus. Trials were not excluded on the basis of quality.

Statistical analyses

Descriptive analyses were performed using Excel 2013. The meta-analytic statistics were performed using the Comprehensive Meta-Analysis program (version 2.2, Biostat™ Inc., Englewood, NJ, USA) using a random-effects model. Descriptive data of the treatment groups and participants are reported as mean ± standard deviation (SD). The standardized mean difference effect size was adopted to quantify changes in performance following acute ED intake. This effect size was defined as the standardized mean difference in pre- versus post-ED intake on performance measurement, divided by the pretest SD. The experimental effect size was described by the difference between the experimental and placebo groups/sessions. Therefore, the paired difference (experimental mean − placebo mean) and paired difference SD [experimental SD^2 + placebo SD^2 − (2 × inter-trial correlation × experimental SD × placebo SD)]$^{1/2}$ were initially calculated. Following this, the standardized mean difference [paired difference × (2 – 2 × inter-trial correlation)$^{1/2}$ ÷ paired difference SD] and standardized mean difference SE [(1/n + standardized mean difference^2) ÷ (2 × n)$^{1/2}$ × (2 – 2 × inter-trial correlation)]$^{1/2}$ were determined. When the study provided only the standard error value, the SD was calculated by multiplying the standard error by the sample n.

Moderator analyses were used to explain variability in effect sizes for the investigated outcome, using weighted meta-regression random models with maximum likelihood estimation [26]. Variables included as potential moderators of effect sizes were age, body mass, caffeine dosage, taurine dosage, publication year, impact factor (*Journal Citation Reports*) and quality of the studies (PEDro Scale). The subgroup analysis included: endurance exercise tests (cycle ergometer vs. running/treadmill), sprints [cycle ergometer or Wingate test vs. running (agility tests and repeated sprints)], muscle strength and endurance (dynamic vs. concentric vs. isometric), jumping (15-s maximal jump test; vertical jump; counter-movement jump; squat-jump) and sport-specific actions (cycling; running; jumping). In the sport-specific actions, maximal distance/velocity in simulated games, running (distance in 5, 10 and 18 km), cycling and specific jumps (volleyball and badminton) were included. Potential differences between subgroup variables were tested using the *Q* test based ANOVA.

The *Q* statistic was calculated to verify whether the degree of similarity in the observed effect sizes was significant [27]. The *Q* statistic was then converted into a standardized measure of homogeneity (I^2 statistic) and corresponding confidence interval (95 % CI) to gauge the level of heterogeneity in the included sample. The I^2 *statistic* between 25 and 50 % represents small amounts of inconsistency, whereas between 50–75 and >75 % represents medium to large amounts of heterogeneity.

The effect of publication bias on the primary meta-analyses was addressed by combining a funnel plot assessment with the Duval and Tweedie's trim and fill correction [28]. In all statistical analysis, a value of $p < 0.05$ was considered to allocate significant differences.

Results

Descriptions of included studies

The general data of the studies included in this review are depicted in Table 1; a total of 34 studies, published between 1998 and 2015, were included in the analysis which allowed 90 comparisons. The total sample consisted of 653 subjects (505 men, 129 women and 19 non-characterized). Twenty-one studies used samples of healthy athletes (four studies with cyclists, three with soccer players, two in volleyball, two with cyclists/triathletes, two with runners/triathletes, one with runners, one with swimmers, one with field hockey players, one with football players, one with rugby players, one with rugby-seven players, one with badminton players and one with strength/power athletes), and the other studies used physically active and healthy samples. The mean age was between 19 and 29 years in 29 studies; between 30 and 39 years in three studies and over 40 years in one study. Body weight ranged from a mean of 57.8 to 100.3 kg. In 17 studies, the ED dosage was fixed as an "absolute dose" for all individuals. In the remaining studies, the ED dosage was standardized in relation to body mass as a "relative dose". In this case, we multiplied the dosage by the mean body weight to obtain the absolute amount of caffeine/taurine consumed by the study participants. All investigations included specific information about the amount of caffeine administered, while 28 studies reported the quantity of taurine intake. In this context, the quantity of caffeine ranged from 40 and 325 mg and amount of taurine ranged from 71 to 3105 mg. In 30 studies, the timing for ED intake was set before exercise (between 10 and 90 min before the onset of experimental measurements). In four studies, the ED was provided before and during exercise. The publication impact factor ranged between 0.18 and 3.983 points; and two studies were not published in journals with impact factor. The PEDro Scale score ranged from 7 to 10. Twenty-six studies used a double-blind crossover design; three studies used single-blind crossover; three studies used crossover; one study used double-blind independent groups and one study used independent groups.

Physical performance meta-analysis

Figures 2, 3, 4, 5 and 6 show the overall effect of EDs intake on endurance exercise test, jumping, muscle strength and endurance, sport-specific actions and sprinting. The overall effect was significant ($p < 0.001$) for all types of performances except for sprinting ($p = 0.06$). Table 2 shows the comparisons between the trials with EDs intake versus placebo/control trials for the different types of performance analyzed. The comparisons in the subgroups of performance were also shown in Table 2; for muscle strength and endurance, there were significant effects for dynamic ($p < 0.001$) and isometric contractions ($p = 0.002$). The *Q* test based ANOVA also showed that dynamic contractions were significantly greater than isometric ($p = 0.03$) and concentric ($p = 0.01$). Regarding the endurance exercise tests, the intake of EDs produced significant effects for the experimental trials performed on a cycle ergometer ($p = 0.04$) and running/treadmill ($p = 0.010$). The analysis of trials that used jumps to assess the ergogenicity of EDs also showed a significant effect on this type of performance ($p < 0.001$). In sprinting, independent of the fact that the overall effect was not significant, the tests performed on the cycle ergometer presented a significant ergogenic effect in the trials with EDs ($p = 0.040$). In sport-specific actions, significant effects were observed for cycling ($p < 0.001$) and running ($p < 0.001$); and the *Q* based ANOVA test also showed that the effects on cycling were greater than on jumping ($p = 0.004$) and running ($p = 0.020$). The I^2 *statistic*, as can be observed in Table 2, demonstrated low heterogeneity for jumping and sprinting; and medium heterogeneity for muscle strength/endurance, endurance exercise tests and sport-specific actions. Publication bias was assessed by

Table 1 General characteristics of the studies included

Study	Impact factor	PEDro Scale	Research design	Subjects characteristics included in the analysis	No of experimental interventions	Caffeine dosage	Taurine dosage	Time of ingestion before the experimental session (s)	Exercise/performance test
Abian et al. [5]	2.246	10	Double-blind, crossover	15 male elite badminton players; 25.4 years; 174.1 cm; 71.8 kg.	9	3 mg kg^{-1}	18.7 mg kg^{-1}	60 min	Handgrip test, jumps, agility *t* test
Alford et al. [6]	3.293	10	Double-blind, crossover	7 males and 7 females (~23 years) and 7 males and 5 females (~20 years)	2	80 mg	1000 mg	30 min	Aerobic and anaerobic endurance on cycloergometer
An et al. [37]	3.794	8	Independent groups	15 males divided in 3 groups (~20 years; ~176 cm; ~72 kg)	2	1.25 and 2.5 mg kg^{-1}	–	60 min	Treadmill maximal test
Astorino et al. [17]	2.293	8	Single-blind, crossover	15 females collegiate soccer players (19.5 years; 168.4 cm; 63.4 kg)	3	80 mg	1000 mg	60 min	Agility *t* test
Candow et al. [22]	2.075	10	Double-blind, crossover	9 male and 8 female physically active; 21 years; 73.4 kg; 175.1 cm	1	2 mg kg^{-1}	25 mg kg^{-1}	60 min	Run time-to-exhaustion treadmill test
Cureton et al. [38]	2.28	10	Double-blind, crossover	16 male cyclists; 27 years; 177 cm; 72 kg.	2	195 mg	1.92 g	6 ml kg^{-1} 10 min before and 3 ml kg^{-1} every 15 min during the cycling test	Maximal voluntary isometric contraction and 135 min of cycling on a cycloergometer
Dall'Agnol and Souza [39]	0.18	10	Double-blind, crossover	20 male physically active; 26 years; 174 cm; 72.2 kg.	1	160 mg	2 g	60 min	Incremental test on cycloergometer
Del Coso et al. [40]	2.66	10	Double-blind, crossover	15 male college volleyball players; 21.8 years; 180 cm; 79.6 kg	5	3 mg kg^{-1}	18.7 mg kg^{-1}	60 min	Standing spike test, jumps and agility *t* test
Del Coso et al. [41]	2.442	10	Double-blind, crossover	13 male field hockey players; 23.2 years;76.1 kg	4	3 mg kg^{-1}	18.7 mg kg^{-1}	60 min	2 × 25 min simulated field hockey game (total distance covered during the game, distance covered at high intensity running, distance covered at moderate intensity, distance covered at sprinting)
Del Coso et al. [14]	3.234	9	Crossover	19 semiprofessional soccers players (21 years; 173 cm; 67 kg)	4	3 mg kg^{-1}	Not cited	60 min	15-s maximal jump test, 7 × 30 m sprint test and simulated soccer game

Table 1 continued

Study	Impact factor	PEDro Scale	Research design	Subjects characteristics included in the analysis	No of experimental interventions	Caffeine dosage	Taurine dosage	Time of ingestion before the experimental session (s)	Exercise/performance test
Del Coso et al. [16]	1.91	10	Double-blind, crossover	9 male and 3 female physically active; 30 years; 173 cm; 69 kg	4	1 and 3 mg kg^{-1}	2000 mg	60 min	Half-squat and bench press power load-test
Del Coso et al. [12]	3.29	10	Double-blind, crossover	16 female seven-rugby athletes; 23 years; 166 cm; 66 kg	3	3 mg kg^{-1}	2000 mg	60 min	15-s maximal jump test, 6 × 30 m sprint test and 3 seven-rugby games
Del Coso et al. [15]	2.339	9	Crossover	26 males rugby athletes; 25 years; 180 cm; 93 kg	1	3 mg kg^{-1}	2000 mg	60 min	2 × 30 min simulated rugby match (total running distance)
Eckerson et al. [34]	2.075	10	Double-blind, crossover	17 male physically active; 21 years; 180.4 cm; 85.5 kg	2	160 mg	2000 mg	60 min	Bench press (1RM and maximal repetitions at 70 % 1RM)
Ganio et al. [42]	2.442	10	Double-blind crossover	14 male cyclists; 27 years.; 179.2 cm; 73.1 kg	2	125 mg L^{-1}	1.92 g L^{-1}	6 ml kg^{-1} immediately before and 3 ml kg^{-1} every 15 min during the exercises	Submaximal 120 min cycling + 15 min performance trial; and maximum voluntary leg isometric extension
Goel et al. [43]	–	10	Double-blind crossover	10 males (20.9 years; 179.2 cm; 69.5 kg) and 10 females (20.4 years; 164 cm; 59.8 kg)	2	2 mg kg^{-1}	–	60 min	Handgrip test
Gwachan and Wagner [44]	2.44	10	Double-blind crossover	20 male football players; 19.7 years; 184.9 cm; 100.3 kg	6	120 mg	200 mg	~60 min	Running-based anaerobic sprint test*
Hoffman et al. [45]	1.908	10	Double-blind crossover	12 male strength/power athletes (21.1 years; 179.8 cm; 88.6 kg)	1	158 mg	–	10 min	Average of 3 Wingate anaerobic power tests
Ivy et al. [46]	2.442	10	Double-blind crossover	6 male and 6 female cyclists; 27.3 years; 68.9 kg	1	160 mg	2000 mg	40 min	Cycling time-trial performance (complete a standardized amount of work equal to 1 h of cycling at 70 % Wmax)
Kammerer et al. [23]	1.908	10	Double-blind crossover	14 male Colombian army soldiers; 20 years. 170.7 cm; 68 kg	5	80 mg	0 and 1000 mg	45 min	VO_{2max} time-to-exhaustion handgrip test vertical. jump
Kovacs et al. [31]	3.056	10	Double-blind crossover	15 male triathletes or cyclists; 23.3 years; 185 cm; 72.6 kg	3	150, 225 and 320 mg L^{-1}.	70 mg L^{-1}	8 ml kg^{-1} 35 min before and 3 ml kg^{-1} every 20 min	1-h time-trial. cycling performance

Table 1 continued

Study	Impact factor	PEDro Scale	Research design	Subjects characteristics included in the analysis	No of experimental interventions	Caffeine dosage	Taurine dosage	Time of ingestion before the experimental session (s)	Exercise/performance test
Lara et al. [13]	1.221	10	Double-blind crossover	18 female soccer players; 21 years; 161 cm; 57.8 kg	3	3 mg kg^{-1}	18.7 mg kg^{-1}	60 min	Countermovement jump; 7 × 30 m maximal. running speed test; 2 × 40 min simulated soccer game.
Lara et al. [47]	3.45	10	Double-blind crossover	14 male sprint swimmers; 20.2 years; 183 cm; 73.9 kg	5	3 mg kg^{-1}	18.7 mg kg^{-1}	60 min	Countermovement jump; handgrip test (right and left hand); 50 m simulated swimming competition and swim at maximal. intensity in a swim ergometer.
Nelson et al. [48]	1.908	10	Double-blind crossover	8 male and 7 female recreationally active; 25.5 years; 77.9 kg	1	2 mg kg^{-1}	25 mg kg^{-1}	60 min	Ride time-to-exhaustion on cycloergometer
Van Nieuwenhoven et al. [49]	2.06	9	Crossover	90 male and 8 female competitive or recreational runners and triathletes; 41 years; 178 cm; 72 kg	1	150 mg	–	150 ml 10 min before + 150 ml at 4.5 km 9 km and 13.5 km	18-km run
Pérez-López et al. [18]	3.983	10	Double-blind crossover	13 elite female volleyball players; 25.2 years; 174 cm; 64.4 kg	5	3 mg kg^{-1}	18.7 mg kg^{-1}	60 min	Standing spike jumps handgrip test and agility *t* test
Pettitt et al. [50]	2.075	10	Double-blind crossover	5 male and 3 female recreationally trained; 23 years; 177.3 cm; 73.6 kg	2	76 mg	1000 mg	35 min	Submaximal test on a cycloergometer
Phillips et al. [51]	2.07	9	Single-blind crossover	11 male cyclists; 33.4 years; 181 cm; 81 kg	1	160 mg	1200 mg	50 min	25-mile simulated cycling road race
Quinlivan et al. [21]	2.662	10	Double-blind crossover	11 male cyclists and triathletes; 31.6 years; 82.6 kg	1	3 mg kg^{-1}	37.6 mg kg^{-1}	90 min	40-km cycling time-trial
Rahnama et al. [52]	0.65	10	Double-blind crossover	10 male student athletes; 22.4 years; 180.8 cm; 74.2 kg	2	75 and 85 mg	1000 mg	40 min	Bruce treadmill test
Schubert et al. [19]	3.27	7	Single-blind crossover	6 male runners; 22.5 years; 179.2 cm; 65.4 kg	2	80 and 140 mg	1000 and 0 mg	~60 min	5-km treadmill time-trial

Table 1 continued

Study	Impact factor	PEDro Scale	Research design	Subjects characteristics included in the analysis	No of experimental interventions	Caffeine dosage	Taurine dosage	Time of ingestion before the experimental session (s)	Exercise/performance test
Sünram-Lea et al. [30]	3.87	10	Double-blind independent groups	71 males and 10 females; 26 years; 178 cm; 80.59 kg divided into three groups	2	40 and 80 mg	–	~75 min	Handgrip test (dominant hand)
Umaña-Alvarado et al. [20]	–	10	Double-blind crossover	11 male runners or triathletes; 30.1 years; ~68 kg	1	32 mg/100 mL	400 mg/100 mL	6 mL kg^{-1} 30 min	10 km cross country run
Ratamess et al. [53]	2.442	10	Double-blind crossover	8 male resistance trained; 20.5 years; 184.0 cm; 91.2 kg	1	110 mg	1500 mg	20 min	Total. repetitions after 6 sets of squat with 75 % 1RM

RM repetitions maximal

* Running-based anaerobic sprint test = six 35-m sprints with 10 s of rest interval between sprints

examining a funnel plot of standard error versus effect size. Asymmetry was observed in the funnel plot, and the Duval and Tweedie's trim and fill correction for the overall effect size were calculated. The adjustment to overall effect was from 0.39 to 0.40, with no effect on the *p* value.

Table 3 presents the values of the moderating variables addressed by the meta-regression analysis. Overall, significant positive associations were identified for the impact factor (slope = 0.11; $p = 0.001$) and taurine dosage (slope = 0.0001; $p = 0.04$). In this context, for each unit increase in impact factor, there was an increase of 0.11 in effect size, and for a 1 mg increase in taurine intake, there was a 0.0001 increase in effect size.

Discussion

The results of the present study were that, overall, the consumption of EDs that contained caffeine increased performance in muscle strength and endurance exercises, endurance exercise testing, jumping protocols and sport-specific actions, at least when compared to trials in which a placebo or control drink was administered. In relation to these results, performance is associated in physiological terms with the quantity of taurine and methodologically with the impact factor of the journal in which the articles were published.

The current analysis showed that EDs ingestion increased performance in a wide variety of physical and sport situations (Table 2), but this ergogenic effect was not produced by the amount of caffeine administered because the caffeine dosage was not associated with the increases in performance. That is, performance does not seem to be influenced by high or low quantities of this substance. In isolation, caffeine in low doses (approximately 200 mg) can increase performance [29] and in the present investigation, we observed studies using caffeine doses between 40 [30] and 325 mg [31]. However, it is important to emphasize that caffeine was not analyzed separately in the present study, since EDs contain a combination of ingredients. In this context, we have two hypotheses: (1) the increase in performance really does not depend on the quantity of caffeine, as previously found for endurance performance [32]; or (2) other substances in EDs, besides caffeine, could contribute to the increased performance. Apparently, our second hypothesis was confirmed by the analysis with regard to taurine. The increase in dosage of taurine in the EDs demonstrated a significant association with performance. In the present study, the taurine dosage ranged from 71.15 [31] to 3105.76 mg [21]. Generally, taurine is ingested in combination with other ingredients, such as caffeine and carbohydrates. Therefore, few studies have examined the isolated effects of taurine on performance. However, it is

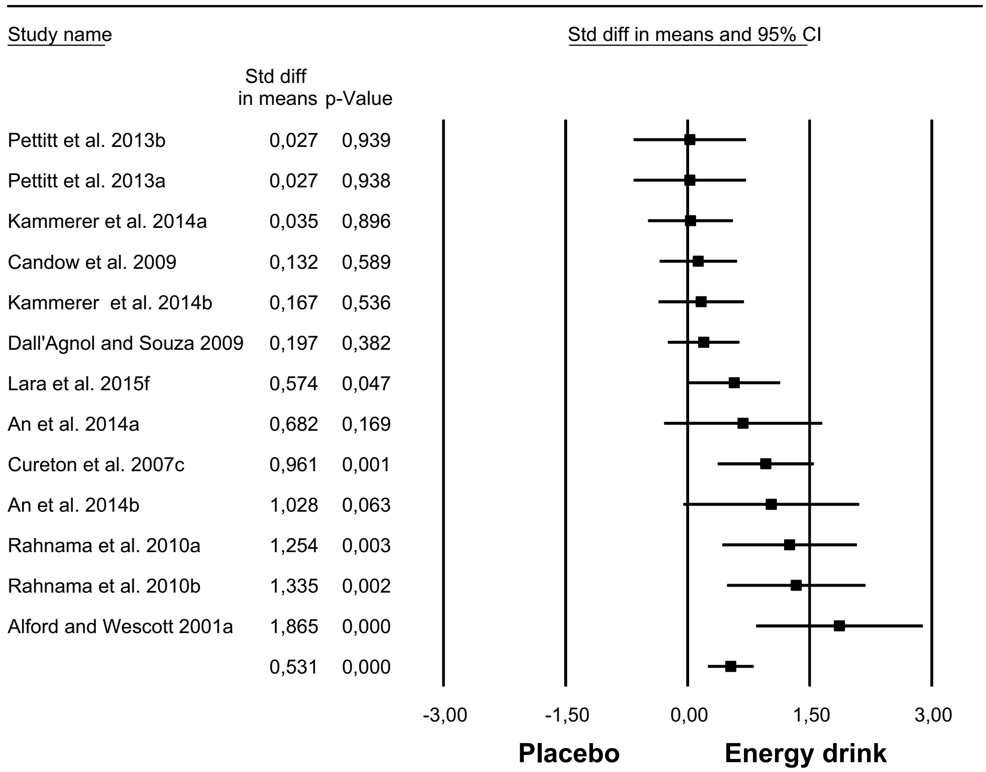


Fig. 2 Effect of caffeine-containing energy drink on endurance exercise test. *Letters* indicate the number of trials of the same study

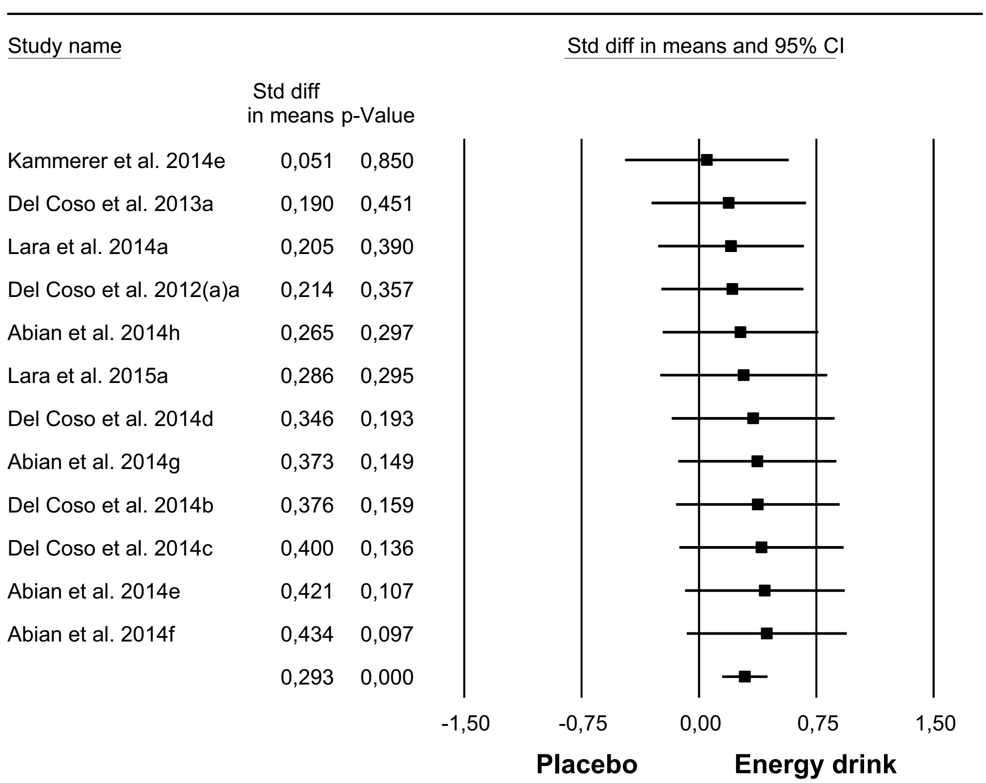


Fig. 3 Effect of caffeine-containing energy drinks on jumping. *Letters* indicate the number of trials of the same study; *letters in parentheses* indicate the number of studies published in the same year

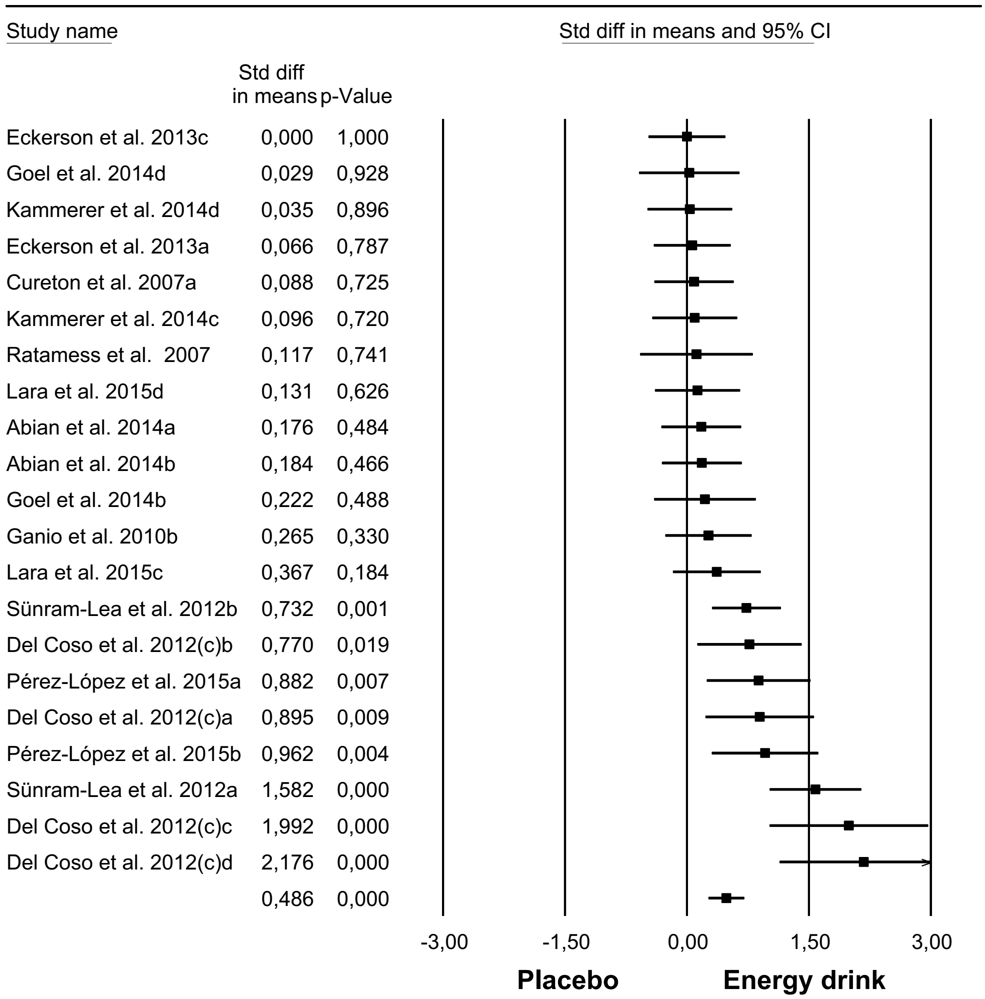


Fig. 4 Effect of caffeine-containing energy drinks on muscle strength and endurance. *Letters* indicate the number of trials of the same study; *letters in parentheses* indicate the number of studies published in the same year

believed that taurine can enhance performance due to the greater ability to generate power through increased calcium regulation [33]. In this context, taurine in high concentrations could increase the calcium accumulation rate in the sarcoplasmic reticulum in type I and type II muscle fibers, which may favor the process of excitation–contraction of skeletal muscles [34]. Additionally, some evidence suggests the interaction of taurine with neurotransmitter receptors in the central nervous system [35]. However, the physiological mechanisms regarding the central effect of taurine on muscular performance are still inconsistent.

In methodological terms, the quality of the studies, assessed through the PEDro Scale, demonstrated no significant association in the overall effect. In fact, the studies included in this systematic review were classified as having relatively high levels of quality. The variation between these values was small, which could have made it difficult to identify a significant association between study quality and performance. In a way, the quality of the studies reflects the quality of the publication, e.g., the impact factor of the journal. Of the 34 studies included in this systematic review, only two were not published in journals with impact factor. On the other hand, unlike the quality of the studies, the impact factor presented a significant association with performance. Thus, the greatest effect sizes were found in journals with a higher impact factor. Our hypothesis is that journals with a higher impact factor have stricter criteria regarding methodological design and experimental procedures, allowing the identification of more consistent results.

In the present review, the analysis included investigations published between 1998 and 2015, i.e., a period of 17 years. Of these investigations, 67 % were published in the last five years. However, the year of publication of the study presented no significant association with performance. The high concentration of studies in a short time

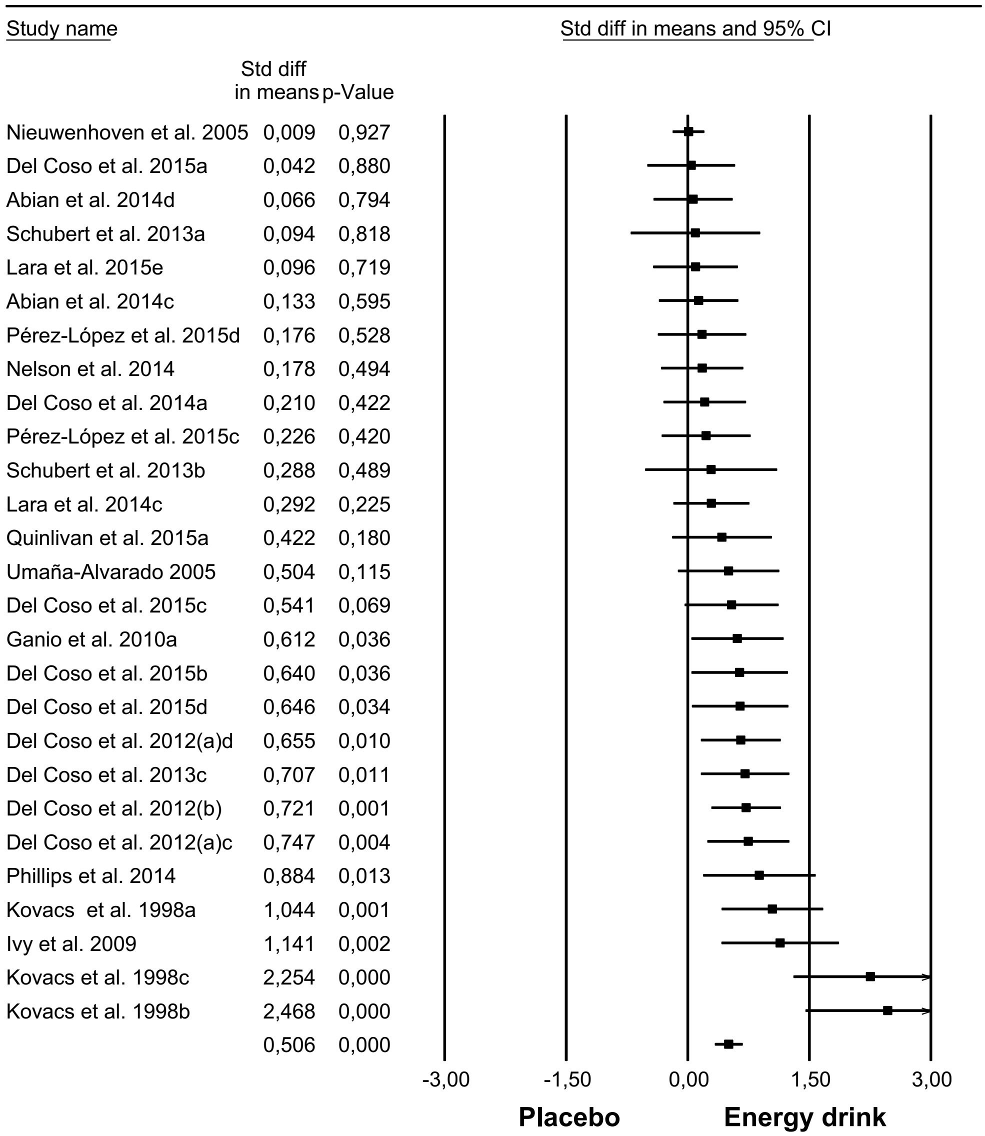


Fig. 5 Effect of caffeine-containing energy drink on sport-specific actions. *Letters* indicate the number of trials of the same study; *letters in parentheses* indicate the number of studies published in the same year

leads us to two conclusions: (1) Currently, there is great interest from researchers on the subject; (2) such studies do not necessarily present large effect sizes in relation to earlier studies. In fact, the I^2 statistic showed mean values of heterogeneity for the subgroups muscle strength and endurance (68.38 %), endurance exercise tests (58.21 %) and sport-specific actions (63.99 %). The interpretation of these values suggests that the confidence intervals of the studies are not completely overlapping and this demonstrates inconsistency in the results that did not occur by chance. Thus, even if the majority of studies have been published in the last 5 years, more experiments are necessary to increase the consistency of the confidence intervals of the studies.

Age and body weight presented no association with performance, probably because all the studies included relatively young, trained subjects without the presence of overweight/obesity. In this context, there are insufficient data to analyze the effects of ED intake on performance in individuals with different age ranges and body compositions. Thus, the outcomes of the present review and meta-analysis should be applied to young and relatively trained subjects, while it is necessary to obtain more information to elucidate the effectiveness of EDs to increase performance in older and less fit individuals.

As for the subgroup analysis, the current investigation showed that isometric strength and dynamic strength were positively and significantly influenced by the intake of

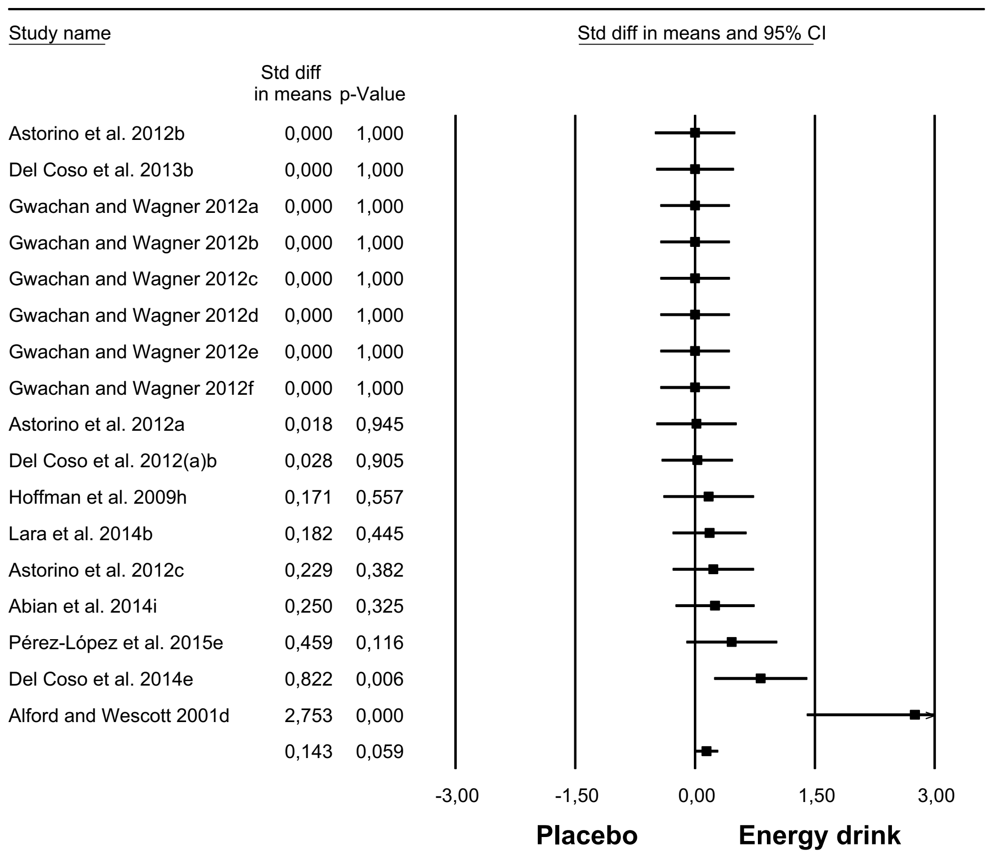


Fig. 6 Effect of caffeine-containing energy drink on sprinting. *Letters* indicate the number of trials of the same study; *letters in parentheses* indicate the number of studies published in the same year

EDs, although this ergogenic effect was not found in trials entailing concentric strength actions. Only three concentric strength trials were included in the analysis, and this may have affected the results. However, it is important to note that in the present review, only one trial [34] analyzed the maximal dynamic strength (1RM). For this reason, all examples of dynamic strength (maximal and repetitions to failure) were included in the mathematical model. Thus, the influence of EDs on 1RM strength is not yet established. As well as strength, a significant effect of ED intake was observed on jump performance. However, for the jumping analysis, high homogeneity was identified among the included trials (I^2 statistic = 0.0). This suggests that these findings are highly consistent, with overlapping confidence intervals. This fact could be explained as there is less variation in the execution of jumps than in muscle strength and endurance tests.

On the other hand, there was no significant difference for the sprints. Although the subgroup analysis demonstrated a significant effect for sprints performed on a cycle ergometer, this can be explained by the fact that only two trials were included; and one [6] presented an effect size which was greatly shifted to the right in relation to the other trial. Therefore, it still cannot be stated that ED increases sprint performance on a cycle ergometer. Sprints can be considered as performances that require high muscular contraction like the demands for muscle strength/endurance and jumping. However, the high muscular contraction demand occurs early in the sprint test and reduces over time in accordance with the increased speed [36]. Therefore, our hypothesis is that EDs do not interfere with movement velocity and therefore have no effect on sprinting.

In relation to the endurance exercise test, overall, a significant effect on performance was identified. The subgroup analysis showed that the effect remained significant in both the running/treadmill and the cycle ergometer. Unlike the high muscular contraction demands which also demonstrated a significant effect (muscle strength/endurance and jumping), the maximum test presents a different characteristic of physical demand (endurance). In this context, the results indicate that EDs may favor performance in endurance activities. Similarly, overall, the effect size was significant for sport-specific actions; and the subgroup analysis showed that cycling and running activities maintained a significant effect size. Both cycling and running are endurance demanding activities, agreeing with the findings in the

Table 2 Subgroup analyses of categorical variables

	No. of trials	I^2 statistic	Effect size (95 % CI)	p value	Q test based ANOVA
Muscle strength and endurance—overall effect	21	68.38	0.49 (0.29–0.54)	<0.001	Dynamic > isometric ($p = 0.03$)
Concentric	3		0.11 (−0.41 to 0.62)	NS	Dynamic > concentric ($p = 0.01$)
Dynamic	5		1.04 (0.56–1.53)	<0.001	
Isometric	13		0.41 (0.16–0.67)	0.002	
Endurance exercise tests—overall effect	13	58.21	0.53 (0.25–0.61)	<0.001	
Cycle ergometer	5		0.52 (0.02–1.01)	0.04	
Running/treadmill	7		0.56 (0.13–1.00)	0.01	
Swimming	1		–	–	
Jumping—overall effect	12	0.00	0.29 (0.15–0.44)	0.01	
Sprinting—overall effect	17	34.35	0.14 (0.005–0.24)	NS	
Cycle ergometer	2		0.64 (0.05–1.23)	0.04	
Running	15		0.11 (−0.04 to 0.26)	NS	
Sport-specific actions—overall effect	27	63.99	0.51 (0.28–0.67)	<0.001	Cycling > jump ($p = 0.004$)
Cycling	8		0.94 (0.62–1.26)	<0.001	Cycling > running ($p = 0.02$)
Running	13		0.45 (0.22–0.67)	<0.001	
Jump	5		0.16 (−0.19 to 0.51)	NS	
Swimming	1		–	–	

Table 3 Meta-regression analysis of continuous variables

Variable	Slope	p value
PEDro Scale	0.04	NS
Impact factor	0.11	0.001
Publication year	−0.02	NS
Body mass (kg)	−0.004	NS
Age (years)	0.001	NS
Caffeine dosage (mg)	0.0009	NS
Taurine dosage (mg)	0.0001	0.04

maximum test. On the other hand, the sport-specific actions jumps did not show a significant effect. The difference in the results between the sport-specific actions jumps and the traditional jumps (previously discussed) can be explained by the reduced number of trials (5 vs. 12, respectively). Visually, the sport-specific actions jumps presented similar confidence intervals, suggesting good consistency. However, the small number of trials can weaken the statistical analysis and hinder the identification of significant values.

Regardless of the results presented herein, it is necessary to mention some limitations of the review: (1) the lack of inter-trial correlation: A lack of inter-trial correlation is relatively common in meta-analyses of studies since the original studies do not usually present these values or do not provide enough data with which to calculate them. Considering that the inter-trial correlation is a necessary value to calculate the effect size, we used the intermediate value of 0.5. However, the effect size could be altered with different inter-trial correlations; (2) outcomes presented by the authors in relation to performance: Some studies provided a relatively large number of outcomes from the same exercise/test. The inclusion of all the provided outcomes would increase the number of comparisons and possibly influence the overall effect size. However, decisions regarding data extraction were resolved as a group and we chose to extract the most important outcome of each exercise/test performed; (3) physiological mechanisms related to ED and performance: The majority of the studies did not examine the physiological mechanisms related to increased performance through ED intake. Due to the relatively small number of studies which addressed this point and the differences in the variables analyzed, we chose not to include the physiological mechanisms in the mathematical model analysis; (4) inclusion of different outcomes in the same mathematical analysis: The grouping of outcomes in a homogeneous manner would provide groups with very few trials. For example, for dynamic strength, we included maximum strength and repetitions to fatigue in the same analysis. Hence, we chose to group the outcomes by the type of requirement, considering that in this way, we would have a greater number of trials to strengthen the analysis and (5) total energy intake: Some studies have used calorie-free flavored drinks as placebo; in others studies, ED and placebo were matched for energy. However, the most of the studies included in our systematic review did not provide the total energy intake (either ED or placebo). Therefore, the influence of ED/placebo calories on performance is still unknown.

Conclusion

The present review and meta-analysis showed that EDs intake improved performance in several physical and sport situations that included muscle strength protocols, jumping, endurance exercise tests and sport-specific action, and taurine dosage influenced the outcome. However, a larger number of studies are needed with physical requirements grouped more specifically to provide more robust data.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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