International Journal of Sport Nutrition and Exercise Metabolism, 2021, 31, 321-328
https://doi.org/10.1123/ijsnem.2020-0363

Human Kinetics
ORIGINAL RESEARCH

Habitual Caffeine Consumption Does Not Interfere With the Acute Caffeine Supplementation Effects on Strength Endurance and Jumping Performance in Trained Individuals

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The long-standing caffeine habituation paradigm was never investigated in strength endurance and jumping exercise performance through a straightforward methodology. The authors examined if habitual caffeine consumption would influence the caffeine ergogenic effects on strength endurance and jumping performance as well as perceptual responses. Thirty-six strength-trained individuals were mathematically allocated into tertiles according to their habitual caffeine consumption: low (20 ± 11 mg/day), moderate (88 ± 33 mg/day), and high consumers (281 ± 167 mg/day). Then, in a double-blind, crossover, counterbalanced fashion, they performed a countermovement vertical jump test and a strength endurance test either after caffeine (6 mg/kg) and placebo supplementation or after no supplementation (control). Perceptual responses such as ratings of perceived exertion and pain were measured at the termination of the exercises. Acute caffeine supplementation improved countermovement vertical jump performance ($p = .001$) and total repetitions ($p = .004$), regardless of caffeine habituation. Accordingly, analysis of absolute change from the control session showed that caffeine promoted a significantly greater improvement in both countermovement vertical jump performance ($p = .004$) and total repetitions ($p = .0001$) compared with placebo. Caffeine did not affect the rating of perceived exertion and pain in any exercise tests, irrespective of tertiles (for all comparisons, $p > .05$ for both measures). Caffeine side effects were similar in low, moderate, and high caffeine consumers. These results show that habitual caffeine consumption does not influence the potential of caffeine as an ergogenic aid in strength endurance and jumping exercise performance, thus challenging recommendations to withdraw from the habitual caffeine consumption before supplementing with caffeine.

Keywords*:* ergogenic, muscle endurance, placebo, power

It is consensually agreed that caffeine potentiates performance through its effects on the central nervous system, as caffeine antagonizes the A_1 and A_{2A} adenosine receptors (Fredholm et al., 1999), reducing the inhibition on neuronal synapsis. Moreover, perceptual responses to exercise, such as ratings of perceived exertion (RPE) and pain are also expected to be lowered with caffeine supplementation (Duncan et al., 2013; Duncan & Oxford, 2012). The ergogenic effects of caffeine supplementation have been well described in a variety of exercises, although systematic reviews have highlighted that these effects may vary greatly from one exercise mode to another (Grgic et al., 2020). In this regard, one of the factors that have been pointed out to influence the potential of caffeine as an ergogenic aid is the caffeine habituation hypothesis.

Early studies with animal models found that higher long-term doses of caffeine induced an upregulation of the A_1 and A_{2A} adenosine receptors expression in vascular and neural tissues (Boulenger et al., 1983; Marangos et al., 1984), indicating that the higher caffeine consumption, the higher tolerance to its effects. These results may have led to a long-standing paradigm that individuals habituated to consume caffeine would be less responsive to caffeine ergogenic effects when compared to nonhabituated counterparts. As a consequence, practical suggestions have emerged recommending precompetition caffeine withdrawal to maximize the caffeine ergogenicity (Sokmen et al., 2008). However, the available evidence in humans has indicated conflicting results, as some results suggested (Beaumont et al., 2017; Bell & McLellan, 2002; Dodd et al., 1991; Evans et al., 2018; Lara et al., 2019) while others refuted (Gonçalves et al., 2017; Grgic & Mikulic, 2020; Jordan et al., 2012; Sabol et al., 2019) the notion of a negative interference of caffeine habituation on the caffeine ergogenicity.

The controversy involving this topic is likely related to a number of methodological issues (Pickering & Grgic, 2019), such as (a) low sample sizes, (b) women being investigated without menstrual cycle control, (c) the use of high-variability exercise tests, (d) insufficient familiarization sessions, (e) the use of nonvalidated questionnaires to assess habitual caffeine intake, (f) dichotomous stratification of caffeine habituation, (g) inadequate blinding efficacy report, and (h) lack of assessment of expectations toward caffeine

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effects. A recent study by Gonçalves et al. (2017) was probably the only one to design a comprehensive methodology to mitigate these biases. Using a reliable endurance cycling time trial, a validated questionnaire to assess the habitual caffeine consumption, and reporting the blinding efficacy regarding the caffeine intake, they observed that habitual caffeine consumption had no effect on the caffeine's ergogenic aid, thus challenging the notion of a caffeine habituation hypothesis in endurance exercise performance. Similar methodology may be applied to unravel the caffeine habituation hypothesis in other exercise modes such as strength and jumping exercises.

Strength and jumping exercises compose training routines of different populations as they are usually recommended to improve muscle strength and hypertrophy (Evans, 2019) as well as sport-related performance (Oxfeldt et al., 2019). It has been shown that caffeine increases muscle endurance (Duncan et al., 2013) and mean power (Astorino et al., 2011) in repetitions-to-failure and all-out tests, respectively, while reducing and/or maintaining RPE and pain. However, we have no knowledge of studies investigating the caffeine habituation hypothesis in strength endurance and jumping performance through a straightforward methodology to control for possible source of bias.

Therefore, the present study aimed to test if caffeine habituation would actually influence the potential of caffeine as an ergogenic aid to improve strength endurance and jumping performance and reduce perceptual responses such as RPE and pain. Using a straightforward methodology as previously used (Gonçalves et al., 2017), we hypothesized that caffeine supplementation would improve strength endurance and jumping performance and reduce RPE and pain responses comparably in individuals differently habituated to caffeine.

Material and Methods

Participants

We calculated that 30 participants were required for this study, assuming a power of 0.80, between-trial correlation of .90 (Sabol et al., 2019), the effect size of 0.20 (Grgic et al., 2018), and alpha error of .05, in muscle endurance and jumping performance as dependent variables (G*Power software, Heinrich Heine University (HHU), Düsseldorf, Germany). However, considering a possible approximately 20% dropout, 36 individuals were recruited between November and December 2019 from fitness centers and personal training studios to participate in the study. Participants were healthy men (age = 24 ± 5 years; height = 1.75 ± 0.07 m; body weight = 77.3 ± 10.2 kg; body mass index = 25.1 ± 2.6 kg/m^2), engaged in strength training programs for at least 1 year by the time the study was conducted (training experience = 6 ± 4 years; training frequency = 4 ± 1 days/week). To standardize the minimal training level, participants had to minimally lift 1.5 times their body mass in a half-squat exercise (relative to half-squat one-repetition maximum = 1.7 ± 0.2).

Participants self-reported no cardiovascular or neuromuscular disorders or health problems that could affect the responses to caffeine supplementation. The exclusion criteria included the self-reported use of (a) any kind of medicines, (b) dietary supplements (at least 2 months before the study), and (c) anabolic steroids before the study. We verbally checked if they followed the request to maintain similar levels of physical activity throughout the study. Participants were also asked to maintain food habits during the study, confirmed by food recalls. They were fully informed about the risks of the study before providing written consent. The study was approved by the Institutional Ethics Committee (Approval Number: 14246719.2.0000.5512) and conformed to the 2013 version of the *Declaration of Helsinki*.

Experimental Design

This was a double-blind, counterbalanced, crossover study. Participants underwent three experimental trials (separated by at least 4 days apart) after preliminary visits: caffeine supplementation (CAF), placebo supplementation (PLA), and no supplement (control [CON]). Participants were randomly assigned to the experimental trials using a Latin Square model (Kuehl, 2000). In the first preliminary visit, we measured the participants' body mass and height (Sanny, São Bernardo do Campo, Brazil) and one-repetition maximum (1-RM) test performance in a half-squat exercise. Individuals also filled a validated food frequency questionnaire to assess habitual caffeine intake (Bühler et al., 2013). The expectation toward caffeine supplementation was measured through an expectation of treatment scale translated to Portuguese language (Younger et al., 2012). In subsequent preliminary visits, participants were familiarized with 1-RM and strength endurance tests (45° leg press exercise) as well as countermovement vertical jump (CMJ) test, until obtaining an interday performance coefficient of variation ≤5%. Overall, participants got acquainted with the 1-RM, strength endurance, and CMJ tests within 4 (±2), 3 (±2), and 3 (±1) sessions, having a coefficient of variation of 1.9%, 2.3%, and 0.3%, respectively. Then, participants performed the experimental CON, CAF, and PLA trials. Fifty-five minutes after the CAF or PLA ingestion, participants warmed up for 5 min on a treadmill and performed the CMJ test. After a 2-min interval, they performed a specific warm-up in a 45° leg press device, and subsequently, the exercise strength endurance test (i.e., approximately 70 min post-supplementation). Participants were evaluated at the same time of the day (1 p.m. to 6 p.m.) to avoid circadian variation-derived influence (Grgic et al., 2019) after a 6-hr fasting period. Two investigators blinded to the treatment allocation provided supervision and verbal encouragement in all experimental sessions.

Maximum Dynamic Strength Test (1-RM)

Maximum dynamic strength was assessed via 1-RM test in half-squat (Smith Machine; Cybex, Medway, MA) and 45° leg press exercises (Movement, São Paulo, Brazil), being considered as the maximum weight lifted in a single repetition according to procedures described by Brown and Weir (2001). The 1-RM load in the half-squat exercise was used to identify eligible participants, while the 1-RM load in the 45° leg press exercise was used to individualize the strength endurance test loads.

Regarding the half-squat, individuals self-positioned their hands on the bar of the Smith Machine and their feet on the ground before the standardization of the knees' flexion angle at 90°. Positions were determined through a goniometer, having the lateral femoral condyle as the point of intersection when the lateral malleolus and greater trochanter were fixed. Regarding the 45° leg press exercise, participants self-positioned their feet on the platform to standardize the knees' flexion angle at 90°. These individual settings were also used in the strength endurance test and maintained throughout the study.

Countermovement Vertical Jump Test

The CMJ performance was evaluated through the *My Jump 2* (Apple Inc., Cupertino, CA) application (Balsalobre-Fernandez et al., 2015; version 3.2.2), recorded through an iPhone 6s (Apple Inc., Cupertino, CA) at a 240 Hz frequency and 1080 pixel high definition resolution. Evidence of validity and reliability of the *My Jump 2* has been previously reported (Balsalobre-Fernández et al., 2015). The iPhone 6s was attached to a tripod, positioned at a 1.5 m frontal distance from the participant. Video frames were recorded to identify air (i.e., absence of feet contact with the ground) and landing phases (i.e., presence of feet contact with the ground) before determining the CMJ height (expressed in centimeters) through the Bosco's equation (Bosco et al., 1983). The highest value among three maximum CMJ separated by a 2-min interval was recorded for analysis.

Strength Endurance Test

Strength endurance tests followed recommendations by Brown and Weir (2001). Participants performed four sets separated by 2-min intervals of maximal repetitions at 1-RM 70%. They started the set having the knees fully extended, and the concentric failure was determined as the incapacity to perform additional concentric repetitions with the correct technique. The total number of repetitions performed throughout the sets was calculated.

Perceived Exertion and Pain Responses

The RPE and pain responses were assessed immediately after the CMJ and strength endurance tests. The RPE was obtained through the CR10 scale (Borg, 1998), while the pain was assessed with a visual analogic 10-point scale. Participants were instructed to rate RPE and pain scales with standard recommendations. Briefly, the RPE scale ranges from 0 (*absolutely no effort*) to 10 (*maximum effort*). In contrast, the pain scale ranges from 0 (*no pain*) to 10 (*maximum pain*). Importantly, participants were oriented to consider RPE and pain as different exercise-derived sensations, as RPE indicated the conscious sensation of how heavy and strenuous was the exercise-related fatigue produced in the muscles, while pain was described as an unpleasant sensation of pain produced in the thigh (Hollander et al., 2003).

Food and Habitual CAF Consumption Evaluation

Habitual caffeine consumption was assessed by a nutritionist through an adapted version of the food frequency questionnaire (Bühler et al., 2013). This questionnaire quantified portions of the habitual consumption of dietary products containing CAF (expressed as household) according to the following frequency of consumption: (a) more than three times a day, (b) two to three times a day, (c) once a day, (d) five to six times a week, (e) two to four times a week, (f) once a week, (g) three times a month, and (h) rarely or never. The list was composed of 10 high caffeine content dietary products, according to the Food and Drug Administration (Somogyi, 2012) such as: (a) espresso and espresso drinks, (b) brewed coffee, (c) instant coffee, (d) green tea, (e) black tea, (f) energetic drinks, (g) regular and diet colas drinks, (h) dark and milk chocolates, (i) sweet cocoa powder, and (j) caffeine supplements.

Importantly, there is no position stand recommending a consensual classification of habitual versus nonhabitual CAF consumers. Thus, the authors first tested if allocating participants into different percentiles according to their dietary CAF intake would produce differences in strength endurance and jumping exercise performance responses. Due to comparable results across subgroups when separating participants within tertiles, quartiles, and quintiles (data not shown), the authors decided to mathematically allocate them into tertiles to provide more power to the analysis. This resulted in the following subgroups: low consumers (20 ± 11 mg/day; range = 0–39 mg/day; $n = 12$), moderate consumers (88 ± 33 mg/day; range = 44–132 mg/day; $n = 12$), and high consumers (281 ± 167 mg/day; range = 136–645 mg/day; $n = 12$; Table 1).

Participants were instructed to abstain from training and alcohol, as well as from caffeine products, within a 24-hr period before the experimental trials. They were assisted with a comprehensive list of the main caffeine-containing products together with a book, having instructions and illustrations to help them to fill a 24-hr dietary food recall. Food recalls were used to calculate the caloric ingestion as carbohydrate, protein, and fat through the Avanutri online software (Avanutri, Rio de Janeiro, Brazil) before each trial.

Supplementation Protocol and Blinding Assessment

In CAF and PLA trials, participants ingested either 6 mg/kg of anhydrous CAF (Grgic et al., 2020) or PLA (magnesium silicate) formulated as gelatin capsules with identical color and size (Erva da Terra Ltda, São Paulo, Brazil). Capsules were ingested with 500 ml of tap water 60 min before the exercise protocols. Supplements were prepared and administered by a pharmacist not involved in the study. Blinding efficacy was assessed immediately after the experimental trials by asking participants to answer the following questions, having CAF or PLA as possible answers: (a) "Can you answer for sure the supplement that you ingested?" (b) "Which supplement do you think you have ingested?" Furthermore, participants answered a side effect questionnaire immediately after and 24 hr after the experimental trials (Pallarés et al., 2013), containing a nine-item form. Participants used a dichotomous scale to associate items and side effects. Finally, participants had their previous expectation toward caffeine effects evaluated through an adapted version of the Stanford Expectation of Treatment Scale (SETS; Younger et al., 2012), which assessed positive

Table 1 Participant's Baseline Characteristics

Characteristics	Low ($n = 12$)	Moderate ($n = 12$)	High ($n = 12$)
Age (years)	21 ± 3	25 ± 6	26 ± 6
Body weight (kg)	77.2 ± 10.0	77.2 ± 10.2	78.2 ± 11.2
Height (m)	1.77 ± 0.06	1.76 ± 0.07	1.73 ± 0.06
BMI (kg/m^2)	24.8 ± 3.0	24.7 ± 2.0	25.9 ± 2.9
Training experience (years)	6 ± 3	7 ± 6	6 ± 4
Training frequency (days/week)	4 ± 1	4 ± 1	4 ± 1
1-RM squat (kg)	129 ± 24	138 ± 31	134 ± 20
1-RM squat/body weight	1.7 ± 0.2	1.8 ± 0.3	1.7 ± 0.3
1-RM leg press (kg)	380 ± 107	382 ± 103	365 ± 117
1-RM leg press/body weight	4.9 ± 1.3	4.9 ± 0.7	4.6 ± 1.1
Best jump (cm)	41.0 ± 6.4	37.1 ± 9.3	36.8 ± 5.4
Caffeine consumption (mg/day)*	20 ± 12	88 ± 34	281 ± 168

Note. Data are expressed as mean ± *SD*. BMI = body mass index; 1-RM = one-repetition maximum.
*Significant difference between tertiles ($p < .001$).

and negative treatment expectancies through a 7-point Likert-type scale with the following anchors: (1) *strongly disagree*, (2) *moderately disagree*, (3) *slightly disagree*, (4) *neither agree nor disagree*, (5) *slightly agree*, (6) *moderately agree*, and (7) *strongly agree*. The SETS score was added as a covariate of performance outcome analysis.

Statistical Analysis

Data were presented as mean ± standard deviation. Gaussian distribution was previously checked through the Kolmogorov–Smirnov test. One-way analysis of variance, having "consumption" (low, moderate, and high) as a fixed factor, was used to determine differences among tertiles in caffeine consumption and participants' baseline characteristics. A two-way mixed-model having "consumption" and "trial" (CAF, PLA, and CON) as fixed factors was carried out to analyze the influence of habitual CAF consumption on: (a) strength endurance total repetitions, pain, and RPE; (b) CMJ performance, pain, and RPE; and (c) food consumption. Accordingly, a two-way mixed model having "consumption" and "trial" as fixed factors examined the influence of habitual CAF consumption on the absolute changes in total repetitions and CMJ performance (i.e., CAF–CON and PLA–CON). The effects of caffeine expectancies on performance outcomes were verified through a mixed-model analysis of covariance, assuming "SETS score" as a covariate and "trial" as a fixed factor. "Participants" were the random factor in all comparisons. Whenever a significant F value was obtained, a Tukey post hoc test was performed. Additionally, we used the CON trial to calculate the CAF-derived smallest worthwhile change on performance (Hopkins, 2020) and the Fischer Exact Test to determine differences in supplement identification as well as the proportion of individuals improving performance above the smallest worthwhile change among trials. Data were analyzed in SAS statistical software (version 9.3; SAS, Cary, NC) with statistical significance set at $p \leq .05$.

Results

Influence of Habitual CAF Consumption on CMJ Performance, RPE, and Pain Responses to Acute CAF Supplementation

We observed a trial ($p = .017$) but not a consumption main effect ($p = .173$) in CMJ performance, showing that regardless of CAF consumption habituation (low, moderate, and high tertiles), CAF improved CMJ performance when compared to PLA ($p = .027$) and CON ($p = .044$). Importantly, no difference was detected between CON and PLA ($p = .979$). Similarly, we found a trial ($p = .004$) but not a consumption main effect ($p = .802$) in CMJ performance expressed as absolute changes from CON, showing that CAF versus CON differences were greater than PLA versus CON differences, irrespective of CAF consumption. The analysis further showed that four, two, and six participants improved CMJ performance above the smallest worthwhile change with CAF supplementation in low, moderate, and high CAF consumption tertiles, respectively. However, Fisher's Exact Test showed no differences among tertiles in the proportion of individuals improving CMJ performance ($p = .223$). Regarding perceptual responses, neither a trial nor a consumption main effect was observed in RPE ($p = .247$ and $p = .551$, respectively) and pain ($p = .299$ and $p = .467$, respectively). Figure 1 depicts these results.

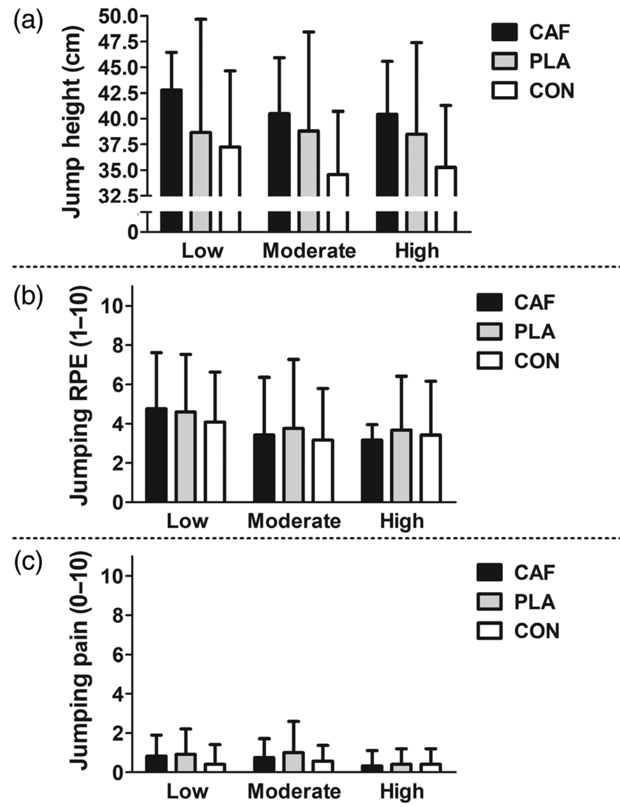

Figure 1 — (a) Countermovement vertical jumping performance in CAF, PLA, or CON separated according to habitual caffeine intake. (b) RPE after the countermovement vertical jumping test with CAF, PLA, or CON separated according to habitual caffeine intake. (c) Pain after the countermovement vertical jumping test with CAF, PLA, or CON separated according to habitual caffeine intake. RPE = rating of perceived exertion; CAF = caffeine supplementation; PLA = placebo supplementation; CON = no supplement (control).

Influence of Habitual CAF Consumption on Total Repetitions, RPE, and Pain Responses to Acute CAF Supplementation

Analysis revealed a trial ($p < .0001$) but not a consumption main effect ($p = .836$) in total repetitions, showing that CAF supplementation improved total repetitions when compared to PLA ($p = .0002$) and CON ($p = .0001$), regardless of CAF consumption habituation (low, moderate, and high tertiles). Moreover, no difference was detected between CON and PLA ($p = .988$). Accordingly, we found a trial ($p = .0001$) but not a consumption main effect ($p = .768$) in total repetitions expressed as absolute changes from CON, showing that CAF versus CON differences were greater than PLA versus CON differences, irrespective of CAF consumption. The analysis also showed that eight, nine, and eight participants improved the total number of repetitions above the smallest worthwhile change with CAF supplementation in low, moderate, and high tertiles, respectively. Fisher's Exact Test showed no differences among tertiles in the proportion of participants improving strength endurance performance with CAF supplementation ($p = .877$). Regarding perceptual variables, neither a trial nor a consumption main effect was observed in RPE ($p = .591$ and $p = .299$, respectively) and pain ($p = .614$ and $p = .770$, respectively). Figure 2 depicts these results.

Food Consumption Analysis

Habitual CAF consumption tertiles showed significant differences in habitual CAF intake (consumption main effect = $p < .0001$) across tertiles (Table 1). However, no significant differences were detected in caloric, carbohydrate, protein, or fat intake between low, moderate, and high CAF consumers in CAF, PLA, and CON trials (Table 2).

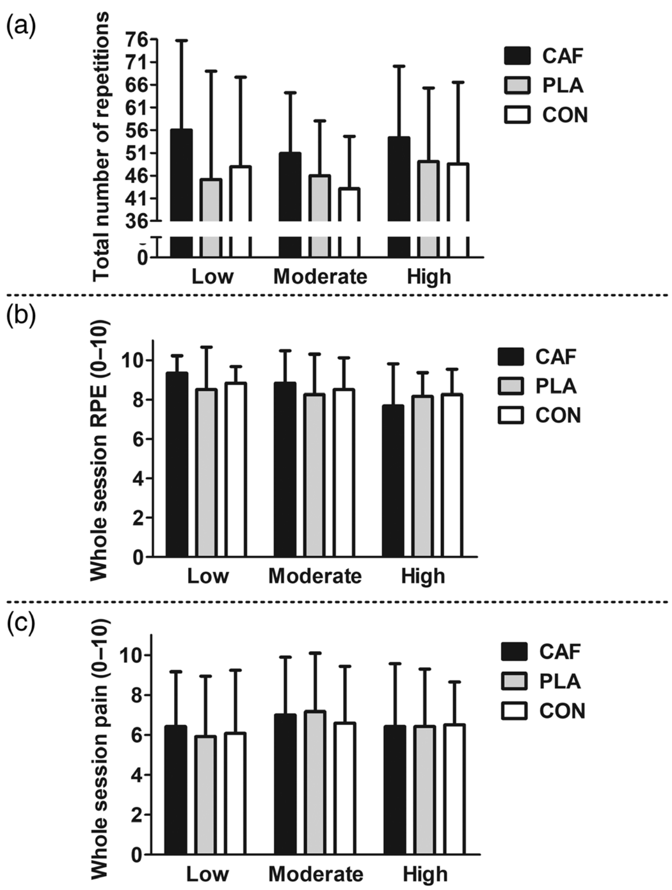

Figure 2 — (a) Total number of repetitions with CAF, PLA, or CON separated according to habitual caffeine intake. (b) RPE after the strength endurance test with CAF, PLA, or CON separated according to habitual caffeine intake. (c) Pain after the strength endurance test with CAF, PLA, or CON separated according to habitual caffeine intake. RPE = rating of perceived exertion; CAF = caffeine supplementation; PLA = placebo supplementation; CON = no supplement (control).

Side Effects, Blinding Efficacy, and Expectation Effects

Increased vigor and perception of performance improvement were the most sensed side effects when participants ingested CAF. However, these side effects were similarly distributed across low, moderate, and high CAF consumption tertiles (Table 3). Moreover, 7 (58%), 8 (66%), and 7 (58%) participants correctly identified CAF and PLA substances in low, moderate, and high CAF consumption tertiles, respectively. However, Fisher's Exact Test revealed no differences in the proportion of supplement identification among tertiles ($p = .889$). The analysis of covariance showed that neither CMJ performance nor total repetitions were significantly influenced by negative ($p = .408$ and $p = .195$, respectively) or positive ($p = .592$ and $p = .201$, respectively) expectation of ingesting CAF.

Discussion

Using a straightforward methodology, we provided unbiased evidence that habitual caffeine consumption influences neither the ergogenic effects of caffeine supplementation on strength endurance and jumping performance nor perceptual responses.

An important bias in caffeine habituation studies is the use of a nonstandard, dichotomous stratification of participants, as most classified habitual consumers as those consuming more than 300 mg/day, and nonhabitual consumers as those consuming less than 50 mg/day (Bell & McLellan, 2002; Dodd et al., 1991; Sabol et al., 2019), thereby disregarding intermediary caffeine intake varying from 50 to 300 mg/day. Importantly, surveys from different countries have observed that most caffeine consumers habitually ingest from 80 to 300 mg/day (Somogyi, 2012; Verster & Koenig, 2018). Therefore, earlier studies may have failed to adequately classify caffeine consumers and yielded biased results. It is worth mentioning that we used a large sample size ($N = 36$), providing sufficient power of analysis even though allocating participants into tertiles. We are unaware of studies examining the caffeine ergogenic effects on strength endurance and jumping performance using a similar sample size (De Salles Painelli et al., 2020).

It has been suggested that the absence of a blinding efficacy report is another important source of bias in the caffeine and performance literature (Shabir et al., 2018). The few strength exercise studies reporting the blinding efficacy have found a high percentage of correct guesses, frequently above 40% (range of 11–85%; De Salles Painelli et al., 2020; Shabir et al., 2018). Even using a randomized clinical trial, we found that approximately 58–66% of the participants correctly guessed the substance they had ingested, perhaps as a result of side effects such as tachycardia, sweating, and increased feelings of vigor and

Table 2 Food Consumption Data Prior to the Experimental Trials

	CAF			PLA			CON		
Variables	**Low**	**Moderate**	**High**	**Low**	**Moderate**	**High**	**Low**	**Moderate**	**High**
Energy (kcal)	2,164 ± 882	2,265 ± 882	1,849 ± 716	2,058 ± 625	2,089 ± 723	2,183 ± 934	1,828 ± 509	2,153 ± 691	1,862 ± 924
Protein (g)	123 ± 60	114 ± 59	119 ± 67	127 ± 63	112 ± 62	123 ± 52	119 ± 56	116 ± 37	126 ± 84
CHO (g)	255 ± 107	274 ± 116	211 ± 96	234 ± 58	267 ± 76	242 ± 124	229 ± 61	269 ± 105	217 ± 125
Fat (g)	72 ± 49	80 ± 35	58 ± 30	67 ± 38	65 ± 33	80 ± 49	48 ± 22	68 ± 34	54 ± 23

Note. Data are expressed as mean ± *SD*. No significant differences were observed across the tertiles and/or experimental conditions. CHO = carbohydrate; CAF = caffeine supplementation; PLA = placebo supplementation; CON = no supplement (control).

Table 3 Frequency (and % of Total Participants) Report of Side Effects in the Placebo and Caffeine Experimental Trials

	Placebo						Caffeine					
	+ 0 hr			+ 24 hr			+ 0 hr			+ 24 hr		
Side effects	Low	Mod	High	Low	Mod	High	Low	Mod	High	Low	Mod	High
Muscle soreness	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Increased urine output	1 (8%)	4 (33%)	3 (25%)	0 (0%)	0 (0%)	1 (8%)	2 (17%)	3 (25%)	2 (17%)	0 (0%)	0 (0%)	2 (17%)
Tachycardia and heart palpitations	0 (0%)	0 (0%)	3 (25%)	0 (0%)	0 (0%)	0 (0%)	2 (17%)	2 (17%)	3 (25%)	1 (8%)	0 (0%)	2 (17%)
Anxiety or nervousness	2 (17%)	1 (8%)	2 (17%)	1 (8%)	0 (0%)	2 (17%)	2 (17%)	5 (41%)	3 (25%)	1 (8%)	1 (8%)	1 (8%)
Headache	0 (0%)	3 (25%)	2 (17%)	0 (0%)	0 (0%)	1 (8%)	2 (17%)	1 (8%)	1 (8%)	2 (17%)	0 (0%)	2 (17%)
Gastrointestinal disturbances	1 (8%)	1 (8%)	1 (8%)	0 (0%)	0 (0%)	0 (0%)	1 (8%)	1 (8%)	1 (8%)	1 (8%)	1 (8%)	1 (8%)
Perception of performance improvement	3 (25%)	5 (41%)	6 (50%)	2 (17%)	2 (17%)	2 (17%)	6 (50%)	6 (50%)	8 (66%)	3 (25%)	2 (17%)	3 (25%)
Increased vigor/activeness	2 (17%)	5 (41%)	5 (41%)	2 (17%)	1 (8%)	3 (25%)	8 (66%)	6 (50%)	8 (66%)	2 (17%)	2 (17%)	3 (25%)
Insomnia	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (8%)	1 (8%)	1 (8%)	0 (0%)	2 (17%)	1 (8%)	2 (17%)
Total reports	9	19	22	5	3	10	24	25	26	12	7	16

Note. Mod = moderate.

wakefulness. However, although randomized clinical trial designs do not control for the caffeine expectancies, it is unlikely that this aspect influenced our results, given that correct guesses were equally distributed across the different caffeine consumption subgroups. The efficacy in blinding participants from caffeine ingestion has been considered a challenge in caffeine studies, as this eventually triggers a powerful placebo effect and potentiates the caffeine's pharmacological ergogenicity (De Salles Painelli et al., 2020). Perhaps, future studies may consider controlled-expectation designs such as caffeine-perceived placebo and use low-side effects caffeine doses to avoid this source of bias in caffeine studies.

In the present study, we adopted methodological cautions to overcome other sources of bias frequently present in caffeine studies. First, only well-trained male individuals were recruited. Second, participants were fully acquainted with performance tests, minimizing the risk of learning effects. Third, validated questionnaires to assess the habitual caffeine consumption (Bühler et al., 2013) were used to better account for possible variations in the caffeine content in different food sources. Finally, as indicated by covariate analysis through SETS score, we found no influence of positive or negative expectations on the caffeine ergogenic effects on performance outcomes, regardless of the caffeine habituation. We are confident this straightforward methodology sorted out previous biases found mainly in studies examining the caffeine habituation hypothesis. It is noteworthy that the habituation hypothesis was mainly supported by studies assessing adenosine receptors expression in animals supplemented with caffeine dosage considered toxic for humans (Boulenger et al., 1983; Marangos et al., 1984). Studies using doses similar to human daily consumption found no evidence of adenosine receptors upregulation in response to habitual caffeine consumption (Johansson et al., 1997).

Furthermore, we found no caffeine effects on perceptual responses. Previous results of RPE and pain responses to caffeine supplementation in strength and jumping exercises are controversial, as some showed a reduced perceptual response together with an improved strength endurance or jumping performance (Duncan & Oxford, 2012; Duncan et al., 2013), while others did not (Astorino et al., 2011; Duncan et al., 2019). A meta-analysis by Doherty and Smith (2005) found that caffeine ingestion reduces the progression of RPE in endurance exercises until reaching maximal tolerable RPE values at the exercise termination. The fact that we assessed perceptual responses at the exercise termination may justify the comparable perceptual responses irrespective of the supplementation, as individuals were oriented to perform both jumping and strength endurance protocols at their maximal capacity.

Despite the use of a valid food frequency questionnaire (Bühler et al., 2013) to assess habitual caffeine intake, we acknowledge that this tool may be subjected to respondent recall-derived errors, somehow limiting the sensitivity to detect varied caffeine contents in different caffeine sources (Areta et al., 2017). A more objective marker to assess habitual caffeine consumption such as urinary or plasma caffeine quantification could be more elucidative.

In conclusion, acute caffeine supplementation was effective to improve strength endurance and jumping performance in trained individuals, irrespective of habitual caffeine consumption. Accordingly, habitual caffeine consumption had comparable effects on RPE and pain responses, although caffeine ingestion itself had no effects on these perceptual variables. These results challenge recommendations to withdraw from the habitual caffeine consumption before supplementing with caffeine to potentiate performance in competition and training (Sokmen et al., 2008).

Acknowledgments

The authors wish to thank all the volunteers for their efforts and the pharmacy Erva da Terra Ltda for the supplement manipulation. The authors also wish to thank Aparecido Costa, Daniel Campos, Marco Antonio Frutuoso, Nilmar Silva, Victoria Ferreti, and Vinicius Gutemberg for their technical contributions. F.O. Pires is grateful to the National Council for Scientific and Technological Development (CNPq—Brazil) for his scholarship of productivity in research (no. 310355/2019-2). The authors declare that they have no conflict of interest. Writing of the original draft, V. de Salles Painelli, E.L. Teixeira, F.O. Pires; conceptualization, V. de Salles Painelli, E.L. Teixeira, F.O. Pires; data curation, B. Tardone, M. Moreno, J. Morandini, V.H. Larrain; investigation, B. Tardone, M. Moreno, J. Morandini, V.H. Larrain, E.L. Teixeira; methodology, B. Tardone, M. Moreno, J. Morandini, V.H. Larrain, V. de Salles Painelli; supervision, E.L. Teixeira, V. de Salles Painelli; formal analysis, V. de Salles Painelli; writing-review and editing, V. de Salles Painelli, F.O. Pires; approval of the final version of the manuscript, B. Tardone, M. Moreno, J. Morandini, V.H. Larrain, E.L. Teixeira, F.O. Pires, V. de Salles Painelli.

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