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Effect of caffeine ingestion on time trial performance in cyclists: a systematic review and meta-analysis

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ABSTRACT

Background: Caffeine, widely recognized as an ergogenic aid, has undergone extensive research, demonstrating its effectiveness to enhance endurance performance. However, there remains a significant gap in systematically evaluating its effects on time trial (TT) performance in cyclists.

Purpose: This meta-analysis aimed to determine the efficacy of caffeine ingestion to increase cycling TT performance in cyclists and to evaluate the optimal dosage range for maximum effect.

Methods: A search of four databases was completed on 1 December 2023. The selected studies comprised crossover, placebo-controlled investigations into the effects of caffeine ingestion on cycling TT performance. Completion time (Time) and mean power output (MPO) were used as performance measures for TT. Meta-analyses were performed using a random-effects model to assess the standardized mean differences (SMD) in individual studies.

Results: Fifteen studies met the inclusion criteria for the meta-analyses. Subgroup analysis showed that moderate doses of caffeine intake (4–6 mg/kg) significantly improved cycling performance (SMD $_{Time}$ = -0.55, 95% confidence interval (CI) = -0.84 ~ -0.26, $p < 0.01$, $I^2 = 35\%$; SMD $_{MPO}$ = 0.44, 95% CI = 0.09 ~ 0.79, $p < 0.05$, $I^2 = 39\%$), while the effects of low doses (1–3 mg/kg) of caffeine were not significant (SMD $_{Time}$ = -0.34, 95% CI = -0.84 ~ 0.17, $p = 0.19$, $I^2 = 0\%$; SMD $_{MPO}$ = 0.31, 95% CI = -0.02 ~ 0.65, $p = 0.07$, $I^2 = 0\%$).

Conclusion: A moderate dosage (4–6 mg/kg) of caffeine, identified as the optimal dose range, can significantly improve the time trial performance of cyclists, while a low dose (1–3 mg/kg) does not yield improvement. In addition, the improvements in

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completion time and mean power output resulting from a moderate dose of caffeine are essentially the same in cycling time trails.

1. Introduction

A mere 1% change in average speed can significant impact medal rankings in highly competitive Olympic endurance events [1]. For instance, during the 2016 Athens Olympics, the champion and runner-up in the team pursuit cycling were separated by just 0.88% in average speed [1]. In the men's individual road race, the top three athletes exhibited a performance gap of less than 0.01% [2]. Given the growing competitiveness in cycling, athletes and coaches continuously seek advantages to maximize their chances of winning by optimizing training methods and/or incorporating sports supplements.

Caffeine, with its convenience and rapid metabolism, has become one of the most popular supplements among athletes [3–5]. Previous meta-analyses have explored the effects of caffeine ingestion on multiple types of exercise performance, such as endurance exercise [1,6–9], team sports [10,11], and resistance exercise [12,13]. The general consensus from these studies is that caffeine can improve endurance exercise performance [1,6–9,14–20].

The meta-analysis exploring the effects of caffeine on endurance performance primarily focuses on two testing protocols, namely time trial (TT) and time to exhaustion (TTE) [6–9,20]. Nevertheless, being a "closed-loop" performance test, TT allows athletes to self-pace and adjust their efforts, simulating the real conditions and characteristics of cycling races unlike "open-loop" tests such as TTE [21]. Additionally, the inclusion criteria in the aforementioned meta-analysis addressing the effect of caffeine on endurance TT performance were often not sufficiently rigorous, resulting in several issues including the inclusion of (1) multiple sports events (i.e. swimming, cycling, rowing, running) [7,8], athletes (i.e. swimmers, cyclists, rowers, runners) [7,8], and forms of caffeine intake (i.e. gum, capsules, liquid) [20], leading to significant research heterogeneity; and (2) co-ingestion of other substances [9], making it difficult to determine the independent effects of caffeine. Furthermore, numerous recent studies have investigated the effect of caffeine intake on TT performance in cyclists, with inconsistent findings [22–26]. Therefore, a meta-analysis is needed to explore the effect of caffeine intake on cyclists' TT performance and provide clarity on the optimal caffeine dosage range.

This meta-analysis aims to review recent studies that investigated caffeine's ergogenic effects on TT performance in cyclists. Our intention is to quantitatively analyze these studies to gauge the extent of caffeine's ergogenic influence on cycling TT performance and identify the optimal dosage. Consequently, we will offer practical guidance for cyclists and coaches seeking to enhance athletic performance through caffeine consumption.

2. Materials and methods

This meta-analysis was conducted following the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and has been

registered in the International System Review Prospective Register (PROSPERO) (CRD42022358446) [27].

2.1. Literature search

We conducted a literature search in PubMed, Web of Science, EMBASE and CNKI (China National Knowledge Infrastructure) databases using the following keywords: *caffeine, coffee, caffeinated, cycling, cyclist, exercise, performance, time trial*. We employed Boolean search syntax ("AND," "OR," "NOT") and tailored our search strategies to each database's characteristics. Considering the sustained interest in caffeine and exercise performance over the past two decades, relevant studies from January 2002 to December 2023 were retrieved. When necessary, we contacted the corresponding authors via e-mail to obtain missing data. Finally, to avoid missing any relevant literature, manual searches were conducted using Google Scholar and Scopus.

2.2. Selection criteria

Inclusion criteria were based on PICOS (participants, interventions, comparators, outcomes, and study design) and included studies that: (1) involved cyclists as participants; (2) examined the effects of isolated caffeine ingestion on TT performance; (3) included a placebo group as a comparator; (4) used completion time (Time) and mean power output (MPO) as evaluation indices of TT performance; (5) utilized a single or double-blind placebo-controlled crossover design. Exclusion criteria were applied to studies that: (1) involved caffeine consumption during the exercise protocol; (2) grouped participants by genotype with different caffeine sensitivity; (3) utilized energy drinks during exercise; (4) conducted studies in extreme environments (high altitude, high or low temperature); (5) consumed caffeine in the form of gum due to its faster absorption rate (5–10 vs. 45–60 min) and differing bioavailability compared to capsules and liquid [28]. Two investigators (B.C. and L.D.) independently selected eligible articles based on the title, abstract and full paper, adhering to the inclusion criteria. For the included studies, the same reviewers independently collected data for use in the meta-analysis.

2.3. Study coding and data extraction

Data extraction was performed to obtain information about participants, interventions, comparisons, outcomes, and study findings. Specifically, the following data were extracted from the included studies: (1) author(s), title, and year of publication; (2) participants' characteristics [e.g. age, maximal oxygen uptake ($\dot{V}O_{2max}$)], habitual caffeine intake); (3) caffeine dose and timing of ingestion; (4) TT performance protocol; (5) main study findings.

2.4. Assessment of methodological quality and statistical analyses

The methodological quality and risk of bias in all eligible studies were assessed according to the criteria outlined in the Cochrane guideline [29]. The Cochrane risk of bias assessment tool evaluates studies for biases, including: (1) random sequence

generation; (2) allocation concealment; (3) blinding of participants and personnel; (4) blinding of outcome assessment; (5) incomplete outcome data; (6) selective reporting; (7) other bias. Ratings for each of category are denoted as either "low risk" ("+"), "high risk" ("-") or "unclear risk" ("?"). Two reviewers (D.L. and C.B.) independently conducted these assessments using Review Manager 5.4 software (Copenhagen: The Nordic Cochrane Center, The Cochrane Collaboration, 2014). Any disagreements regarding quality and risk of bias were resolved through discussion or by a third reviewer (C.Y.).

To gauge the effect of caffeine intake on TT performance, we employed a random-effects model that assigned weights to the selected studies based on their standard deviations, which allowed us to calculate the weighted-mean standardized mean differences (SMD). TT performance was measured in two ways: MPO within a set duration completion time for a specific athletic event. We conducted a meta-analysis utilizing Review Manager 5.4 software. Results are presented as *P*-value, SMD, and 95% confidence interval (CI). An ergogenic effect was considered when the time to complete a set performance decreased with caffeine compared to placebo, or when MPO in a set TT increased with caffeine compared to placebo. Effect sizes were classified as *trivial* (SMD <0.20), *small* (0.20 ≤ SMD < 0.50), *moderate* (0.50 ≤ SMD < 0.80), or *large* (SMD ≥0.80) according to established criteria [30].

We assessed heterogeneity among the included studies using the I^2 statistic as recommended by the Cochrane Collaboration. Heterogeneity levels were categorized as low (I^2 <25%), moderate (25% ≤ I^2 ≤50%), and high (I^2 >50%) [31]. Subgroup analyses were conducted when there were at least three studies to explore potential sources of heterogeneity [30]. Meta-regression analysis was conducted using Stata 14.0 software to examine how factors such as $\dot{V}O_{2max}$, age, and exercise duration affected performance outcomes in TT events for both caffeine and placebo. Funnel plots, Egger's regression, and trim-and-fill tests were employed to assess publication bias.

3. Results

3.1. Study characteristics

Out of 1,749 initially identified studies, we removed duplicates and conducted title and abstract screening (Figure 1). After applying our criteria, we selected 15 articles with a total of 35 effect sizes for quantitative analysis [22–26,32–41].

Table 1 presents the characteristics of all the included studies. A total of 14 studies investigated the effects of caffeine on Time, comprising 18 trials [22–24,26,32–41], while 13 studies examined the effects of caffeine on MPO, comprising 17 trials [22–26,33–37,39–41]. The studies that provided caffeine doses relative to body weight had doses ranging from 1–6 mg/kg. One study used an absolute dose of 200 mg, which is equivalent to a relative dose of 2.5 mg/kg [26]. Fourteen studies administered caffeine supplementation 60 minutes prior to exercise [22–26,32–41], while one study had a scheme of caffeine ingestion 90 minutes before exercise [37]. One study initiated exercise following individual peak serum caffeine concentrations [36]. None of the studies reported commercial sponsorship.

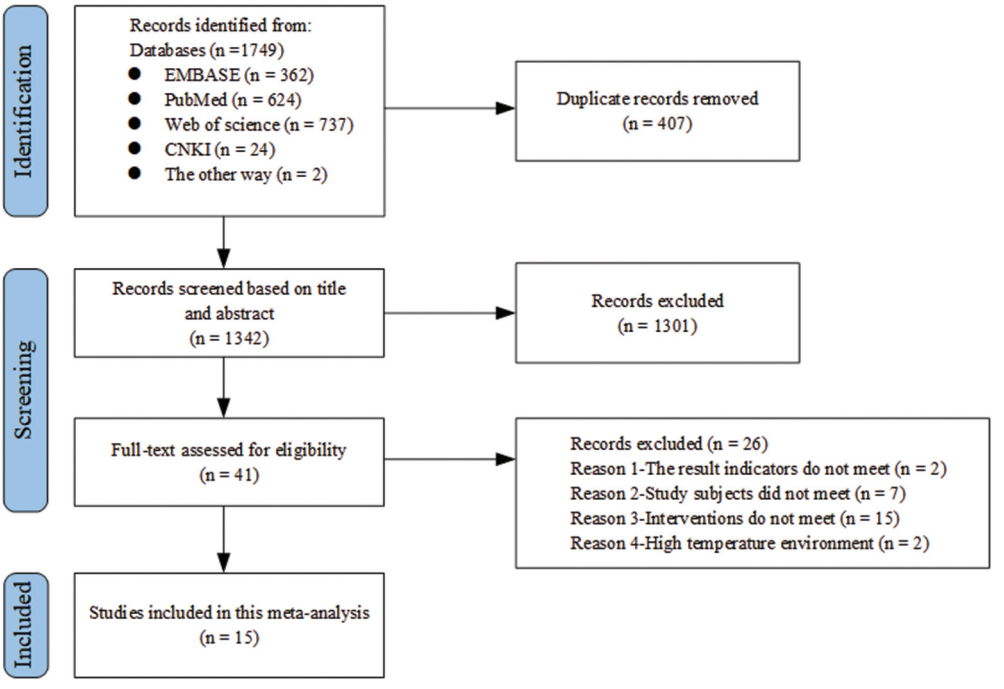

Figure 1. Flow diagram of study selection.

3.2. Quality of study methods

The risk of bias assessment was conducted for the 15 included placebo-controlled crossover trials (Figure 2). Three trials had a low risk of bias, while 12 were deemed to have a moderate risk of bias. Firstly, a slight publication bias may exist in terms of performance outcomes in TT (Time and MPO), as indicated by the funnel plots (Figure 3 and 4). However, funnel plots are subjective inspection methods, and further analysis is required by combining Egger's regression intercept test. Secondly, based on the numerical values of Egger's regression intercept, the Egger's linear regression results for performance outcomes in TT showed a significant difference from zero ($p < 0.05$), suggesting the presence of publication bias. Finally, after conducting trim and fill analysis to assess the impact of publication bias, the overall effects for performance outcomes in TT remained significant, indicating that the study results are not significantly influenced by publication bias and can be considered reliable (Table 2).

3.3. Meta-analysis results

Fourteen placebo-controlled crossover studies, encompassing 18 trials, examined the effect of caffeine on Time (Figure 5) [22–24,26,32–41]. There was a significant effect of caffeine ingestion (1–6 mg/kg) on Time compared to placebo (SMD = −0.50, 95% CI = −0.74 ~ −0.26, $p < 0.001$, $I^2 = 23\%$). Three trials involving 62 participants (31 in the caffeine group and 31 in the placebo group) assessed the effect of a low dose (1–3 mg/kg) of

Table 1. General characteristics of the studies included.

Study	Sample size	Age (years)	VO_{2max} (ml/min/kg)	Habitual caffeine intake (mg/day)	Caffeine withdrawal (h)	Caffeine does (mg/kg)	Timing (min)	Caffeine form	Exercise protocol	Total exercise time (min)	Exercis time (min)	performance % change (Time)	performance % change (MPO)
Acker-Hewitt et al. [22]	10	28 ± 9	66 ± 9	NA	24	6	60	Capsules	20 min 60% W_{max}; 20 Km TT	63.6	43.6	−1.4%	3.8%
Bortolotti et al. [23]	13	26 ± 10	NA	NA	24	6	60	Capsules	20 Km TT	36.4	36.4	−0.5%	−1.1%
Conway et al. [32]	8	26 ± 5	72 ± 6	<250	48	6	60	Capsules	90 min 68% VO_{2max}; 80% $\dot{V}O_{2max}$ ×30 min KJ TT	113.8	23.8	−15.9%	NA
Felippe et al. [39]	11	34 ± 4	55 ± 4	NA	24	5	60	Capsules	4 Km TT	6.6	6.6	−1.7%	4.4%
Goncalves et al. [38] a	14	34 ± 9	50 ± 9	58 ± 29	24	6	60	Capsules	0.85 × W_{max} ×1500 KJ TT	30.3	30.3	−1.6%	NA
Goncalves et al. [38] b	12	37 ± 7	51 ± 6	143 ± 25	24	6	60	Capsules	0.85 × W_{max} ×1500 KJ TT	29.7	29.7	−3.7%	NA
Goncalves et al. [38] c	14	37 ± 8	51 ± 8	351 ± 139	24	6	60	Capsules	0.85 × W_{max} ×1500 KJ TT	30.4	30.4	−1.4%	NA
Hodgson et al. [34]	8	41 ± 7	58 ± 3	≤300	24	5	60	Liquid	30 min 50% W_{max}; 650 KJ TT	68.4	38.4	−4.3%	6.1%
Jenkins et al. [25] a	13	26 ± 7	55 ± 7	132 ± 41	48	1	60	Capsules	15 min 80% $\dot{V}O_{2max}$; 15 min TT	30.0	15.0	NA	−0.7%
Jenkins et al. [25] b	13	26 ± 7	55 ± 7	132 ± 41	48	2	60	Capsules	15 min 80% $\dot{V}O_{2max}$; 15 min TT	30.0	15.0	NA	4.1%
Jenkins et al. [25] c	13	26 ± 7	55 ± 7	132 ± 41	48	3	60	Capsules	15 min 80% $\dot{V}O_{2max}$; 15 min TT	30.0	15.0	NA	3.0%
Kilding et al. [33]	10	24 ± 5	NA	NA	24	3	60	Capsules	20 min 60–65% MPO; 3 Km TT	23.8	3.8	−1.0%	2.1%
Larson et al. [40]	9	34 ± 11	61 ± 6	100–400	12	5	60	Capsules	20 Km TT	33.2	33.2	−3.9%	4.4%

(*Continued*)

Table 1. (Continued).

Study	Sample size	Age (years)	VO_{2max} (ml/min/kg)	Habitual caffeine intake (mg/day)	Caffeine withdrawal (h)	Caffeine does (mg/kg)	Timing (min)	Caffeine form	Exercise protocol	Total exercise time (min)	Exercis time (min)	performance % change (Time)	performance % change (MPO)
Quinlivan et al. [37]	11	32 ± 6	61 ± 8	271 ± 295	24	3	90	Capsules	0.75 × W_{max} ×3600 KJ TT	62.6	62.6	−3.1%	2.8%
Santos et al. [35]	8	33 ± 5	58 ± 6	NA	24	5	60	Capsules	4 Km TT	6.8	6.8	−2.4%	6.3%
Santos et al. [41] a	8	35 ± 5	57 ± 8	NA	24	5	60	Capsules	4 Km TT	6.1	6.1	−1.5%	4.3%
Santos et al. [41] b	8	35 ± 4	49 ± 10	NA	24	5	60	Capsules	4 Km TT	6.7	6.7	−2.5%	6.5%
Skinner et al. [36] a	14	31 ± 5	70 ± 6	NA	48	6	60	Capsules	40 Km TT	57.9	57.9	−2.0%	0.7%
Skinner et al. [36] b	14	31 ± 5	70 ± 6	NA	48	6	120–150	Capsules	40 Km TT	58.5	58.5	−1.1%	3.0%
Spence et al. [26]	10	30 ± 2	59 ± 2	NA	48	2.5	60	Capsules	40 Km TT	74.0	74.0	−1.3%	1.1%
Griest et al. [24]	10	39 ± 15	54 ± 6	253–620	24–28	6	60	Capsules	10 min 55% W_{max};10 Km TT	28.03	18.05	−4.5%	9.3%

"a","b," "c" represents the number of trials of the same study. *F*: Females, *KJ*: Kilojoules, *M*: Males, *MPO*: mean power output, *NA*: no available, *Time*: completion time, *Timing*: time of ingestion before the experimental session, *TT*: time trail, $\dot{V}O_{2max}$: maximal oxygen uptake, W_{max}: work rate max.

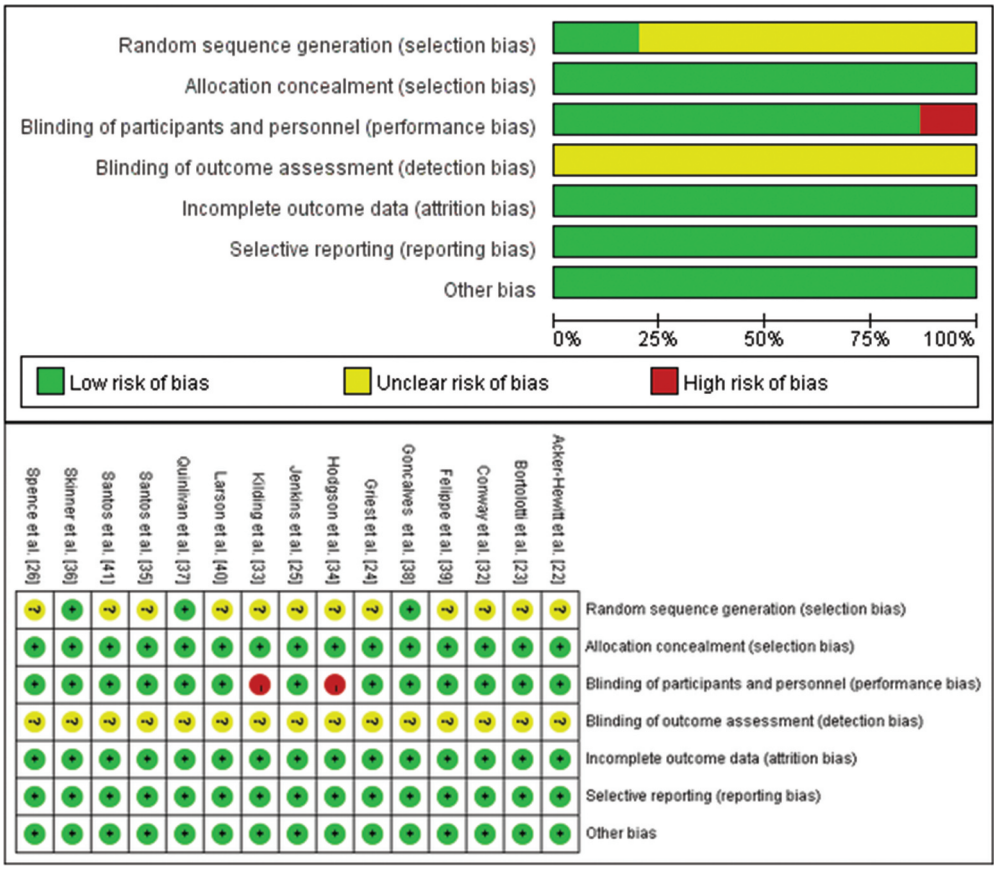

Figure 2. Risk of bias summary of included studies.

caffeine on Time [26,33,37], while 15 trials with 322 participants (161 in the caffeine group and 161 in the placebo group) evaluated the effect of a moderate dose (4–6 mg/kg) of caffeine on Time [22–24,32,34–36,38–41] (Figure 5). Subgroup analysis indicated that moderate dose of caffeine ingestion (4–6 mg/kg) resulted in a significant improvement in Time (SMD = −0.55, 95% CI = −0.84 ~ −0.26, $p < 0.01$, $I^2 = 35\%$) (Figure 5). However, the improvement in Time due to caffeine was not significant when a low dose caffeine (1–3 mg/kg) was administered (SMD = −0.34, 95% CI = −0.84 ~ 0.17, $p > 0.05$, $I^2 = 0\%$) (Figure 5).

Thirteen placebo-controlled crossover studies, encompassing 17 trials, examined the effect of caffeine on MPO [22–26,33–37,39–41] (Figure 6). There was also a significant effect of caffeine ingestion (1–6 mg/kg) on MPO compared to placebo (SMD = 0.37, 95% CI = 0.14 ~ 0.60, $p = 0.002$, $I^2 = 16\%$). Six trials, involving 140 participants (70 in the caffeine group and 70 in the placebo group), assessed the effect of a low dose (1–3 mg/kg) of caffeine on MPO [25,26,33,37]. Additionally, 11 trials with 226 participants (113 in the caffeine group and 113 in the placebo group) evaluated the effect of a moderate dose (4–6 mg/kg) of caffeine on MPO [22–24,34–36,39–41] (Figure 6). Subgroup analysis showed that moderate doses of caffeine intake resulted in a significant improvement in MPO (SMD = 0.44, 95% CI = 0.09 ~ 0.79, $p < 0.05$, $I^2 =$

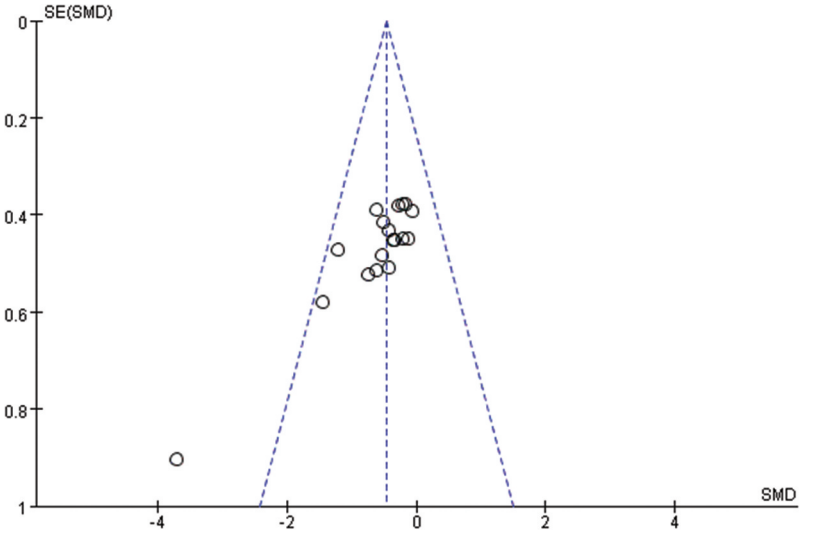

Figure 3. Funnel plot of standard mean difference against standard error for completion time. SE (SMD) Standard error of the mean difference, SMD Standard mean difference.

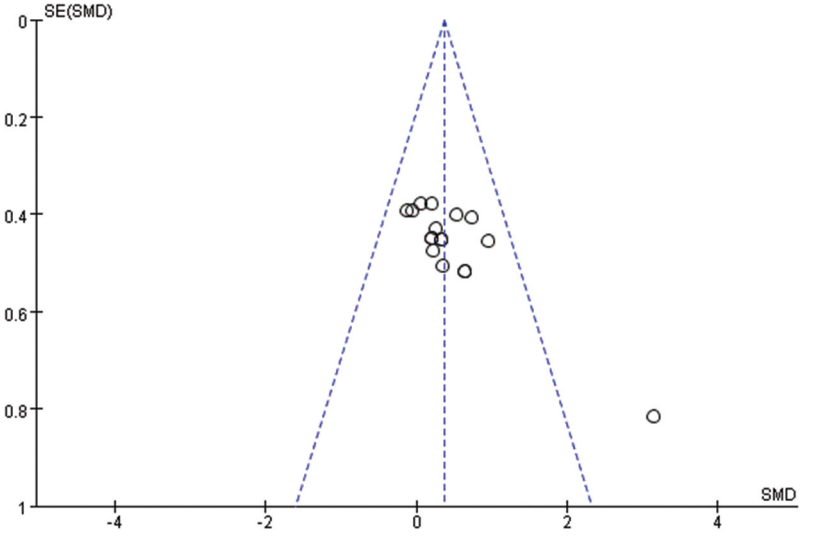

Figure 4. Funnel plot of standard mean difference against standard error for mean power output. SE (SMD) Standard error of the mean difference, SMD Standard mean difference.

39%) (Figure 6). However, the improvement of caffeine on MPO due to caffeine was not significant when a low dose was administered (SMD = 0.31, 95% CI = −0.02 ~ 0.65, $p = 0.07$, $I^2 = 0\%$) (Figure 6).

Meta-regression analysis showed no significant relationship between the effect size of both Time and MPO, and the independent variables: $\dot{V}O_{2max}$ ($P_{MPO} = 0.523$; $P_{Time} = 0.266$), age ($P_{MPO} = 0.199$; $P_{Time} = 0.263$), and exercise duration ($P_{MPO} = 0.932$; $P_{Time} = 0.535$) (Table 3).

Table 2. Duval and Tweedie's trim and fill random effects of time trial results.

Outcome indicators	Potential number of missing studies	Variables	Pooled estimate	95% CI	
				Lower Limit	Upper Limit
Time	3	Observed values	−0.535	−0.790	−0.280
		Adjusted values	−0.641	−0.882	−0.400
MPO	0	Observed values	0.396	0.150	0.642
		Adjusted values	0.396	0.150	0.642

CI: confidence intervals, *MPO*: mean power output, *Time*: completion time.

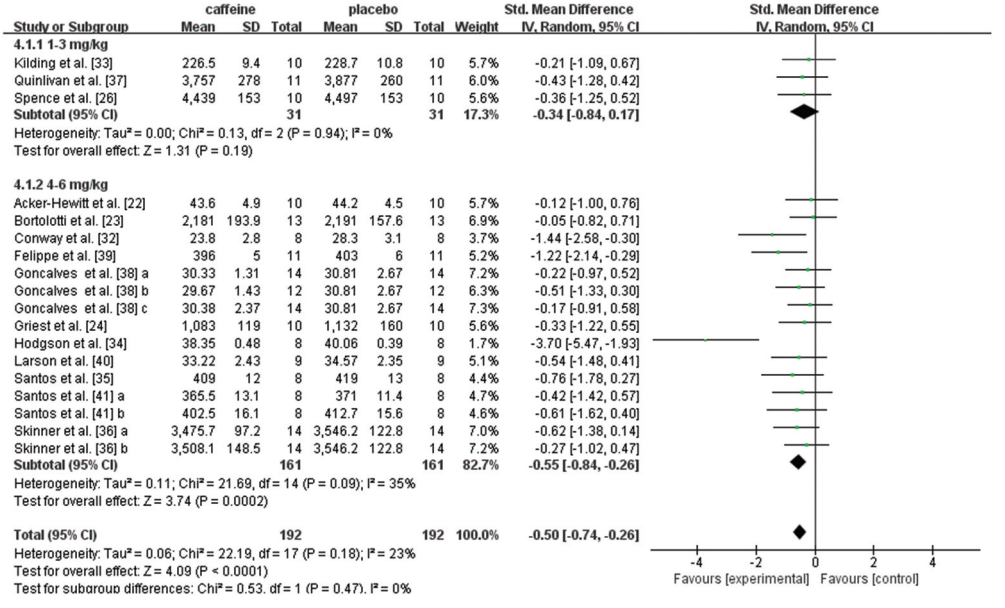

Figure 5. Subgroup analysis of the effects of different caffeine doses intake on time trial performance (completion time) of cyclists. "a", "b," "c" represents the number of trials of the same study. Filled green square represents study-specific estimates, and filled diamond represents pooled estimates of random-effects. Std Mean Difference Standard mean difference, *CI* confidence interval, *SD* standard deviation.

4. Discussion

The aim of this systematic review and meta-analysis was to evaluate the effect of caffeine intake on TT performance in cyclists and determine the optimal dosage range for most pronounced ergogenic effect. We found that a moderate dose (4–6 mg/kg) of caffeine intake significantly improves the TT performance of cyclists (SMD $_{\text{Time}} = -0.55$, $p < 0.01$; SMD $_{\text{MPO}} = 0.44$, $p < 0.05$). Conversely, lower doses (1–3 mg/kg) of caffeine do not result in performance improvement (SMD $_{\text{Time}} = -0.34$, $p = 0.19$; SMD $_{\text{MPO}} = 0.31$, $p = 0.07$).

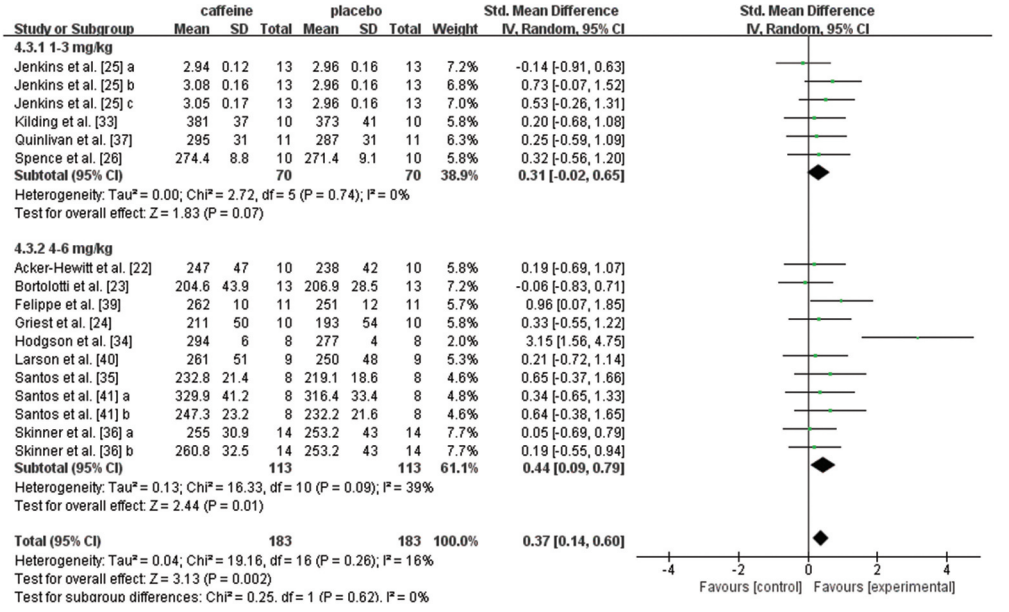

Figure 6. Subgroup analysis of the effects of different caffeine doses intake on time trial performance (mean power output) of cyclists. "a", "b," "c" represents the number of trials of the same study. Filled green square represents study-specific estimates, and filled diamond represents pooled estimates of random-effects. Std Mean Difference Standard mean difference, CI confidence interval, SD standard deviation.

Table 3. Meta-regression analysis of time trial results.

Variables	Outcome indicators	Coefficient	*P* value
age	Time	−0.085	0.263
	MPO	0.048	0.199
$\dot{V}O_{2max}$	Time	−0.039	0.266
	MPO	−0.023	0.523
exercise duration time	Time	0.097	0.535
	MPO	−0.0007	0.932

MPO: mean power output, *Time*: completion time, $\dot{V}O_{2max}$: maximal oxygen uptake.

4.1. Effects of low to moderate dose of caffeine intake on cycling TT performance

Our results indicate that a moderate caffeine dose can improve the TT performance of cyclists (Figure 5 and 6). Our results are consistent with a recent meta-analysis that incorporated various endurance sports (i.e. swimming, cycling, running, double poling and triathlon), which also suggested that a moderate caffeine dose significantly enhances TT performance [8]. However, the overall effect sizes in their study were slightly lower than what we observed (SMD $_{Time}$: 0.41 *vs*. 0.55; SMD $_{MPO}$: 0.24 *vs*. 0.44). This difference could be attributed to the inclusion of different endurance events and exercise in high-temperature environments (~30℃) in their meta-analysis [8,42], potentially reducing the overall effect size. Considering the previously mentioned study conducted under high-temperature conditions, it is noteworthy that caffeine failed to enhance TT performance, as indicated by SMD =

−0.24 [42]. Additionally, a systematic review examining the effect of caffeine on TT performance in rowing, cycling, running, swimming and skiing, also suggested that a moderate caffeine dose is likely to offer the greatest improvement in TT performance compared to low or high doses of caffeine [15]. Our study reaffirms this conclusion, suggesting that compared to a low dose (1–3 mg/kg) a moderate dose of caffeine (4–6 mg/kg) enhances cyclists' TT performance (Figure 5 and 6). This is evident in the greater effect size and mean improvement (SMD $_{Time}$: 0.55 *vs*. 0.34; SMD $_{MPO}$: 0.44 *vs*. 0.31) (Time: 3.2 ± 3.72% *vs*. 1.78 ± 1.15%; MPO: 4.33 ± 1.67% *vs*. 2.08 ± 1.67%). However, a meta-analysis focusing on the effect of caffeine on endurance performance found that the ergogenic effect of caffeine is not significantly dose-dependent [9]. This discrepancy could be due to the low dosage (1–3 mg/kg) of caffeine included in that meta-analysis and the administration of caffeine through energy drinks, which may contain other substances that might interfere with the effects of caffeine.

The larger ergogenic effect of moderate-dose caffeine, compared to low-dose caffeine, on TT performance may be attributed to an increased number of adenosine receptors in cyclists. Caffeine's antagonistic effect on adenosine receptors is a well-established mechanism through which it influences endurance performance [43–47]. Firstly, recent research indicates that endurance athletes who engage in long-term training exhibit adaptive changes to cope with exercise-induced stress, thereby increasing the number of adenosine receptors [48]. Secondly, we found that participants in both the low-dose group (167 ± 70 mg/day) and the moderate-dose group (221 ± 112 mg/day) had a moderate caffeine consumption habit (75–300 mg/day) [49]. Habitual caffeine intake can also enhance athletes' tolerance to caffeine by increasing the number of adenosine receptors [50,51], thereby reducing the ergogenic effect of caffeine on athletic performance [52,53]. Overall, a moderate dosage above 3 mg/kg may be required to effectively block the increased number of adenosine receptors in cyclists, thereby improving TT performance.

4.2. Effects of moderate caffeine dose intake on time and MPO in cycling TT

We observed that both Time and MPO, which are commonly used indicators in cycling TT, showed comparable improvements compared to placebo group (Time: +3.2 ± 3.7%, MPO: +4.3 ± 1.7%). These results are consistent with a meta-analysis that investigated the effects of moderate-dose caffeine on Time and MPO among athletes participating in various endurance events (Time: +2.2 ± 2.6%, MPO: +2.9 ± 2.2%). The comparable improvements in Time and MPO due to caffeine in our study align with research suggesting that a 1% change in power output roughly corresponds to a 1% change in Time [54]. However, another meta-analysis found a more substantial improvement in endurance performance (+22.3% ± 13.3%) in cycling tests compared to placebo trials, which is substantially larger than our observed effects [6]. This discrepancy could be attributed to their inclusion of TTE measurement protocols, where a 1% change in output power leads to a 15% change in Time [54].

4.3. Heterogeneity analysis of moderate-dose caffeine effects on cycling TT performance

Heterogeneity analysis of moderate caffeine dosage on Time and MPO in the included studies showed that I^2 were 35% and 39%, respectively. These values indicate a moderate level of internal heterogeneity in the research results. In contrast, a meta-analysis focusing on the ergogenic effects of moderate-dose caffeine on endurance TT performance revealed a larger level of heterogeneity within the studies ($I^2 = 63\%$) [8]. This disparity may be attributed to the broader inclusion of different endurance events (i.e. swimming, cycling, running, double poling and triathlon) in the aforementioned meta-analysis [8]. To explore potential sources of heterogeneity, we conducted a meta-regression analysis. The results are consistent with other meta-analyses, indicating that age (24–41 years), $\dot{V}O_{2max}$ (49–72 ml/min/kg), and exercise duration (3.8–72 min) do not significantly influence performance improvement observed between caffeine and placebo [6–8]. However, given that the studies included in our analysis shared similar characteristics in terms of these variables, future research should consider broadening the age range, incorporating world-class athletes, and including longer competition durations to further elucidate the impact of these variables on the ergogenic effects of caffeine. Additionally, genetic variations have been found to influence the ergogenic effects of caffeine on athletic performance, which could contribute to the observed heterogeneity in our research [8,55]. Research indicates that individuals carrying the AA genotype exhibit faster caffeine metabolism and higher sensitivity to caffeine compared to individuals with the CC or AC genotypes [56–59]. Finally, other factors such as gender, cigarette smoking, alcohol intake, and the use of hormonal contraceptives may also serve as potential sources of heterogeneity that warrant further exploration [60–62].

5. Practical implications

Our result indicates that a moderate caffeine dosage (4–6 mg/kg) leads to a 2% higher improvement in TT performance compared to a low dosage (1–3 mg/kg). This 2% advantage holds practical relevance, as it could potentially elevate an 8th place finisher's time (57:18) in the men's cycling TT at the 2021 Tokyo Olympics to a top-three finish (56:08) [2]. Existing research has demonstrated that a moderate caffeine dose generally does not produce significant side effects such as gastrointestinal discomfort, lack of concentration, or accelerated fluid loss [18,63,64]. In addition, individuals exhibit variability in their response to caffeine`s ergogenic effects [15,18,19], and an athlete's specific caffeine needs entail a careful balance between maximizing the dose for a meaningful physiological stimulus and preserving overall well-being by avoiding potential side effects. Hence, we recommend that practitioners focus on identifying the optimal caffeine dose for each individual athletes through a series of trials conducted before official competitions. This personalized approach can help ensure that athletes harness the performance-enhancing benefits of caffeine without compromising their health and comfort during competition events.

6. Limitations and future considerations

Although this systematic review rigorously examined the existing literature and strictly adhered to the PRISMA guidelines, there are certain limitations that should be considered [27]. First, our analysis did not include factors such as dietary habit (alcohol and cigarettes), gender, and genetic type, which have been proven to influence the metabolic effects of caffeine [18,60,61]. Future research should take these variables into account to better understand the effects of caffeine on cyclists. Second, our study primarily focused on the effects of caffeine on MPO and Time in cycling TT, omitting investigations into various physiological and psychological indicators such as blood lactate concentration, heart rate, and ratings of perceived fatigue. Incorporating these additional metrics in future studies could provide valuable insights into the ergogenic effects of caffeine among cyclists. Third, cyclists often consume caffeine in combination with other substances during competitions [1]. Therefore, future research should explore the differences in effects resulting from different co-intake strategies. Last, the small number of studies included in the low-dose group analyses may limit our ability to draw definitive conclusions from the obtained outcomes.

7. Conclusion

This systematic review and meta-analysis showed that a moderate dosage (4–6 mg/kg) of caffeine, identified as the optimal dose range, significantly improves the time trial performance of cyclists. Contrastingly, a low dose (1–3 mg/kg) does not yield the same improvement. In addition, the improvements in completion time and mean power output due to a moderate dose of caffeine are essentially equivalent in cycling time trials. These findings could provide a basis for cyclists and coaches to devise more effective caffeine supplementation strategies. However, when tailoring personalized supplement regimens, it is essential to consider individual athlete differences (i.e. gender, dietary habits, and genetic types) to maximize caffeine's ergogenic effects.

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Data availability statement

Data are available on request from the authors

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