ORIGINAL ARTICLE

Effects of caffeine ingestion on performance and biomechanical parameters of running: A randomized crossover trial

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ABSTRACT

This study aimed to assess the impact of 6mg/kg of caffeine (CAFF) on running performance and technique. Using a randomized, double-blind, crossover structure, 14 subjects ran 2.5 kilometres on a treadmill, without (PRE) and with (POST) fatigue, under 3 conditions with 7 days as a wash-out: control (CON), placebo (PLA), and CAFF. CON was always assessed first. The results showed that POST, there was less flight time (d = 0.85), more step rate (d = 0.61-0.62) and less stride length in both legs (d = 0.61-0.63), less knee flexion (d = 0.75), and a slower performance (d = 0.72). Compared to CON, PLA increased contact time in both legs (d = 0.70-1.01) while improving performance (d = 1.00), and CAFF reduced step rate (d = 0.85-0.86) and increased stride length in both legs (d = 0.82-0.86) while also enhancing performance (d = 1.01). CAFF PRE showed a faster time compared to CAFF POST, PLA POST, CON PRE, and CON POST (d = 1.17-1.92), and PLA PRE was faster than CON PRE, CON POST, and CAFF POST (d = 1.19-1.50). In conclusion, CAFF improved running performance compared to CON, suggesting a front-loaded strategy, while PLA also enhanced performance relative to CON. Furthermore, CAFF, PLA, and fatigue modified running kinematics. This trial was prospectively registered on Clinical Trials (NCT06039358; September 2023) and supported by "*AGAUR-FI ajuts*".

Keywords: Biomechanics, Ergogenic aids, Injuries, Sports performance, Sports nutrition.

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INTRODUCTION

Caffeine (CAFF) is one of the few supplements that has been classified as an ergogenic aid, with strong evidence supporting its efficacy and safety (Maughan et al., 2018). Its benefits on performance are accepted to be mainly derived from its effect on the central nervous system as an antagonist at the adenosine receptors, although other mechanisms have also been hypothesized (Guest et al., 2021). Moreover, the reduction of perceived exertion or fatigue during exercise and increased alertness and vigilance have also been reported with CAFF ingestion (Guest et al., 2021; Maughan et al., 2018). However, some of the ergogenic effects of CAFF may be attributable to the placebo (PLA) effect (Marticorena et al., 2021). Endurance exercise is the type of effort in which much of the research on CAFF has been conducted, and improvements of 2-4% have been observed with 3-6mg of CAFF/kg (Guest et al., 2021). More specifically, CAFF may enhance performance over different running distances (Schubert & Astorino, 2013). Additionally, CAFF can improve time to exhaustion in running trials and time to complete endurance running time trials (Wang et al., 2023).

In this regard, running is an increasingly popular physical activity, with a variety of distances to compete in (Schubert & Astorino, 2013; Skypala et al., 2023). However, running-related injuries can be common (Skypala et al., 2023). Different kinematic, kinetic, and spatiotemporal variables have been identified as factors that may increase the risk of running-related injuries (Ceyssens et al., 2019; Willwacher et al., 2022). Besides, one of the leading causes of injuries in running may be neuromuscular fatigue (Encarnación-Martínez et al., 2022). While unfatigued running may allow the maintenance of the preferred movement pattern, fatigue can limit the muscular ability to control joint movement (Encarnación-Martínez et al., 2021), generating modifications in the running biomechanics (Encarnación-Martínez et al., 2021; Skypala et al., 2023). Moreover, metabolic acidosis and neuromuscular fatigue are detrimental to performance in middle-distance running (Schubert & Astorino, 2013).

Taken together, the ergogenic role of CAFF in running performance and the relevance of biomechanics for injury risk highlight a gap in the literature, as few studies have thoroughly examined how CAFF influences running biomechanics. Specifically, this effect has been assessed during the development of a 100-metre and 60-metre sprint running, identifying modifications in its execution (Horiuchi & Nagahara, 2024; Matsumura et al., 2023). Different potential processes have been mentioned to physiologically explain some of these modifications, such as CAFF effects on muscle activation (Horiuchi & Nagahara, 2024; Matsumura et al., 2023) or the calcium release from the sarcoplasmic reticulum (Horiuchi & Nagahara, 2024), which in some cases lead to greater force during muscle contractions (Horiuchi & Nagahara, 2024).

Based on this evidence, while the benefits of CAFF are usually judged solely by performance outcomes, its impact on technique execution has not been clearly studied, which may entail adverse consequences. Therefore, assessing the impact of the cognitive and physiological effects of CAFF on running technique and its preservation in fatiguing circumstances may be interesting due to its aforementioned relation with injury risk. The goal of this study is to determine whether CAFF can modify the performance and technical execution of running in fatigued and non-fatigued conditions in naïve-low CAFF consumers, compared to a PLA and a control (CON). We hypothesize that CAFF generates changes in the technical execution of running in fatigued and unfatigued circumstances due to its physiological effects, potentially benefiting performance and neuromuscular patterns.

MATERIALS AND METHODS

Participants

This study's target population consisted of individuals with an advanced training level, defined as an uninterrupted training time of ≥1 year in their regular exercise modality, and a good technique in the assessed exercises - based on a previous classification (Santos Junior et al., 2021). The exclusion criteria were chosen to diminish interindividual differences in the response to CAFF (Pickering & Kiely, 2018): 1) Being <18 or >30 years old; 2) Relevant medical conditions; 3) Pregnancy; 4) Smoking; 5) Regular medication consumption or its consumption during the study; 6) Regular consumption of ergogenic supplements or its consumption during the study; 7) Habitual CAFF ingestion of >25mg/day-0.99mg/kg/day (not naïve-low consumers (Filip et al., 2020)).

Making an a priori power analysis using G*Power (v. 3.1.9.6, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany), assuming a within repeated measures ANOVA, an effect size (ES) of the CAFF impact of 0.15 (f) (Grgic, 2022), a significance level of .05, a desired power of 0.80, 1 tested group with 6 measurements, and a correlation among repeated measures of 0.90 (Grgic, 2022), the sample size needed would be 11 participants. This study is within a project that assessed the impact of CAFF on running, jumping, and squatting. The sample size was calculated based on the effect of CAFF on the vertical jump height since this performance outcome leads to a more restrictive measurement (running performance ES = 0.39, and correlation = 0.67 (Hurst et al., 2019)). Considering possible dropouts, we recruited 15 athletes. The promotion of the study for the enrolment process was conducted at the University of Vic and other facilities of the city's sports teams using posters. The recruitment period was from October to November 2023. One participant withdrew from the study between the enrolment and the familiarization sessions, due to an injury unrelated to the study. Therefore, 14 volunteers completed the entire study and were included in all the analyses (Figure 1 and Table 1).

Table 1. Baseline data of the participants, by sequence.

Variable	Sequence control-caffeine-placebo	Sequence control-placebo-caffeine
Sex	Male = 7 (100%) Female = 0 (0%)	Male = 4 (57.14%) Female = 3 (42.86%)
Age (years)	22.00 (3.32)	22.14 (3.08)
Height (m)	1.76 (0.06)	1.69 (0.07)
Body mass (kg)	75.53 (8.06)	62.31 (6.33)
Body fat (%)	19.59 (4.34)	22.26 (8.88)
Habitual caffeine intake from foodstuffs (mg/kg/day)	0.20 (0.35)	0.25 (0.31)
Habitual caffeine intake as an ergogenic aid (mg/kg/day)	0.00 (0.00)	0.00 (0.00)

Note. Sex is reported as frequency and (%), while the rest of the values are the mean and (standard deviation). m = Meters. kg = Kilograms. mg = Milligrams.

Measures

The primary outcomes of this study were the effect of CAFF on performance and biomechanics, compared between the 3 sessions, with and without fatigue. The same researcher assessed all the outcomes. The trial protocol consisted of 2.5km running on a treadmill (RAM, Padua, Italy), adapted from previous studies (Dingenen et al., 2018; García-Pinillos et al., 2019): Participants ran with their usual training shoes for 8 minutes at 10.5km/h with 0% slope, the last 30 seconds of which were recorded for further analysis. The movement was filmed in slow-motion at 240fps using a smartphone (iPhone 11 Pro Max, Apple, Cupertino, USA). It was placed on a portable tripod perpendicular to the sagittal plane, 2.79m from the treadmill, and at

a height of 1.16m. After this period, they completed the remaining distance at a self-selected velocity as quickly as possible. They manually modified the treadmill velocity and received standardized verbal feedback. The performance modification outcome was the time to complete the remaining 1.1km after the 8 minutes at 10.5 km/h, measured using a stopwatch.

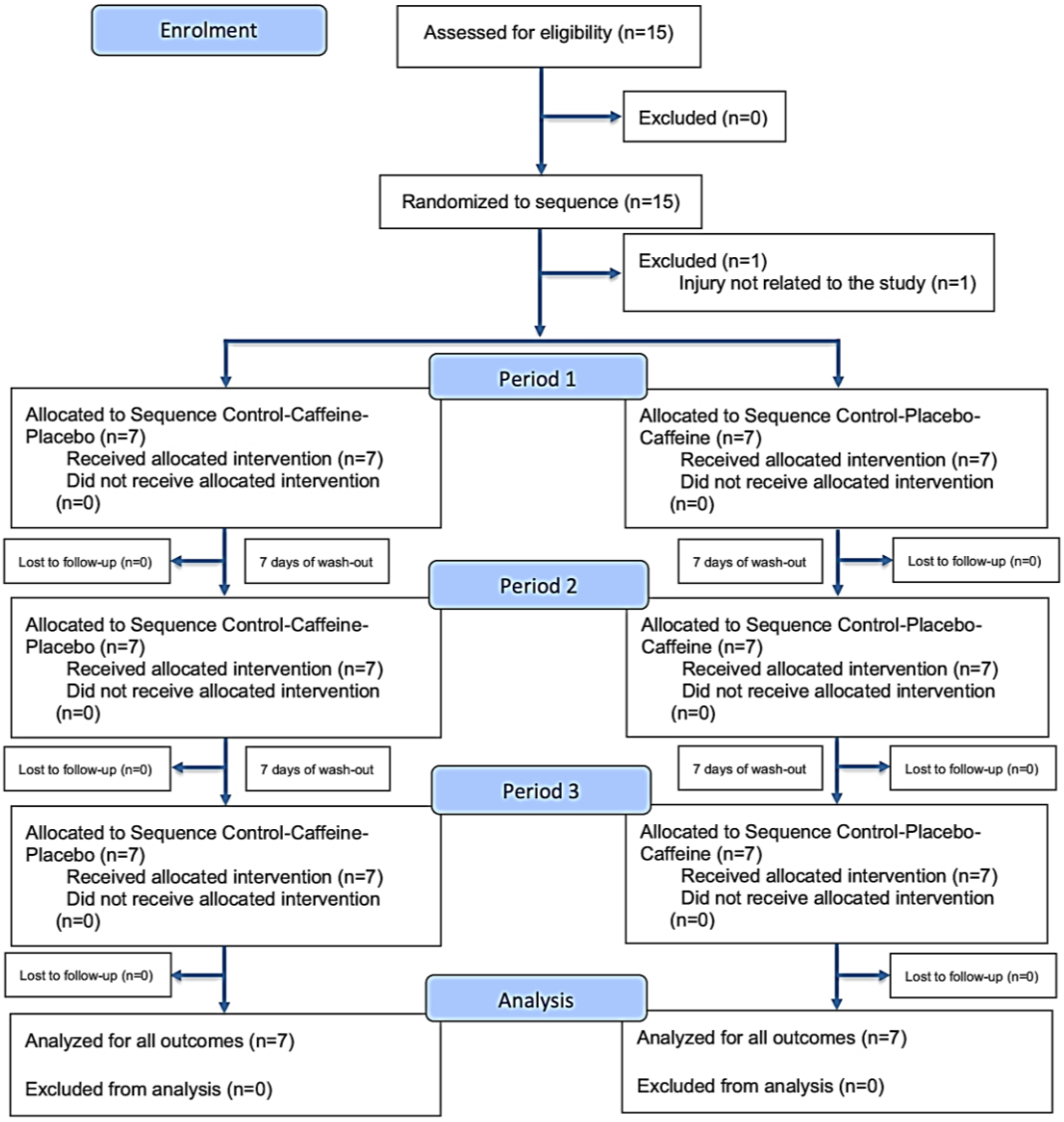

Figure 1. CONSORT flow diagram.

The running technique analysis was conducted using the 30-second recording, performed by a single researcher, and was done using Kinovea (v. 0.9.5), which has shown its validity and reliability (Balsalobre-Fernández et al., 2014; Puig-Diví et al., 2019). The mean values of 10 consecutive strides that did not present remarkable technique abnormalities were analysed. Reflective markers were placed on the participants' right side of the body, always by the same researcher. They were fixed to the greater trochanter (GT), the lateral femoral epicondyle (LFE), the fibular head (FH), and the lateral malleolus (LM). Adhesive spray, tape, and elastic bandages were used to ensure their attachment. The LFE and the FH were localized and marked with the athletes seated with the knee flexed at 90º, while for the other landmarks, they were standing.

The identified variables included two angles measured on the midstance frame (the moment that the knee of the leg not touching the ground is beside the knee of the leg contacting the ground), on the right side of the body. These were the knee angle (angle formed by the GT-LFE line, and the LFE-LM line; ↓ angle - ↑ knee flexion), and the tibial angle (angle formed by a vertical line from the LM and the LM-FH line; ↑ angle - ↑ ankle dorsiflexion). Other spatiotemporal variables were also measured individually for both limbs: step rate (10/duration of the 10 analysed steps), stride length (velocity of the treadmill/step rate), contact time (time from the initial contact to the toe-off (when the foot loses contact from the ground) of the same leg), and flight time (time from the toe-off to the initial contact of the same leg). The feasibility of these variables was tested in a pilot study. Figure 2 presents some of these variables and procedures.

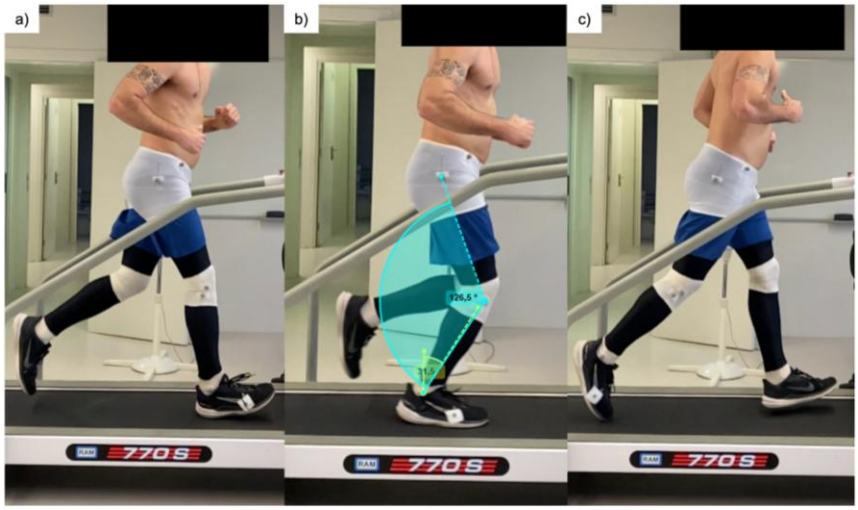

Figure 2. Representative frames showing key time points during running: (a) initial contact, (b) midstance, and (c) toe-off. The midstance frame also illustrates the measurement of knee and tibial angles.

Procedures

Study design

This study is reported under the CONSORT guidelines and their extension for crossover trials (Dwan et al., 2019; Hopewell et al., 2025) (Supplementary Material 1). There was no public or participant involvement in the design, conduct, or reporting of the trial. The structure of the study was a randomized controlled trial, double-blinded, PLA-controlled, with a crossover. The crossover design was chosen to optimize the required sample size (Dwan et al., 2019). This trial registry and protocol were prospectively registered on ClinicalTrials (Identifier: NCT06039358 (https://clinicaltrials.gov/study/NCT06039358); registered September 15, 2023). No important changes were performed from the pre-specified procedures.

In this article, only the results of the running exercise of the study are reported. It is important to mention that for each participant, the order of the exercises was randomized (https://www.random.org) and kept constant across all sessions. The data of the study were collected in the sports sciences laboratories of the University of Vic-Central University of Catalonia (Vic, Spain). No interim analyses were performed or planned. The occurrence of severe side effects from the trial was the only criterion for early stopping the study. The study protocol was reviewed and approved by the University of Vic-Central University of Catalonia Research Ethics Committee (internal code: 238/2022) before its commencement. The study respected the rights of the participants at all times and adhered to the principles outlined in the Declaration of Helsinki and its subsequent amendments.

The athletes visited the centre individually 5 times during the study. The first one was the enrolment session, in which their eligibility criteria were checked. Afterward, once the athletes were informed about the study procedures, they provided their informed consent before their inclusion in it. Finally, their baseline characteristics were registered: self-reported biological sex, age, height measured using a stadiometer (GIMA, Gessate, Italy), body mass and body fat measured using a bioimpedance scale (Omron, Kyoto, Japan), habitual CAFF consumption from foodstuffs (Bühler et al., 2014), and habitual use of CAFF as an ergogenic aid for training and competitions.

During the following weeks, the other 4 sessions (≈3 hours each) took place: familiarization, CON, CAFF consumption, and PLA consumption. The last two sessions mentioned, which were identical and assessed together with the CON one, were performed in a randomized and double-blind fashion. CON session was always the first one assessed, similar to previous research (Filip-Stachnik et al., 2022; Horiuchi & Nagahara, 2024; Hurst et al., 2019). All the sessions were separated by at least 7 days to allow recovery and a wash-out period to avoid carry-over effects (Magkos & Kavouras, 2005). The follow-up period finished the morning after the assessed sessions.

Each participant performed the assessed sessions at a consistent time of the day. During the 48 hours before each session, the athletes were requested not to undergo fatiguing physical activities nor ingest CAFF. During the 24 hours preceding the sessions, they were also not allowed to consume alcohol and had to ingest a diet as similar as possible. To do so, dietary intake information from 24-hour recalls was recorded and evaluated using the ASA24 Dietary Assessment Tool (v. 2022, National Cancer Institute, Maryland, United States of America). Finally, 2-4 hours before the beginning of the sessions, they had to eat their habitual pre-exercise meal.

As part of the familiarization session, the participants completed the 48-hour CAFF control and the ASA24 assessments, and their records were replicated in subsequent sessions. Afterward, they were informed about the benefits of CAFF for exercise performance to achieve a more consistent PLA effect. Then, they standardized the size of 5 elastic bandages, practiced the warm-up protocol used in the remaining sessions, and adjusted the execution and intensity of the squat movement performed in this study. Finally, the exercises performed in the other sessions were demonstrated, and participants practiced them until an acceptable technique was achieved.

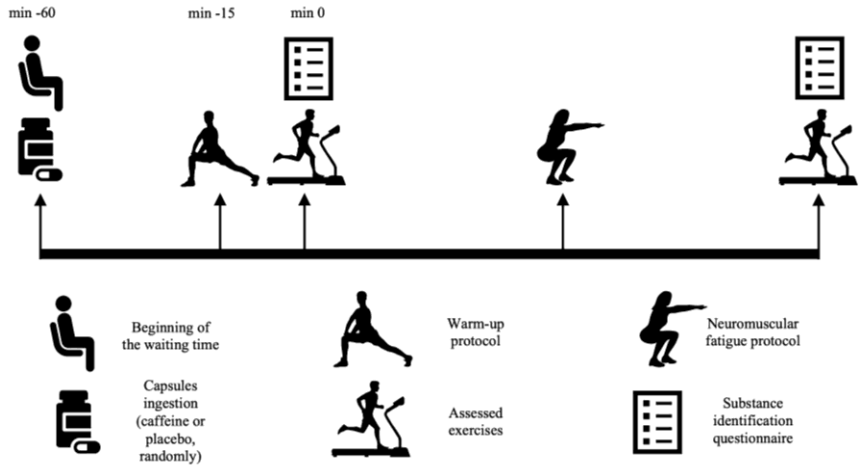

Figure 3. Assessed sessions structure.

The structure of the assessed sessions is outlined in Figure 3. There was no resting period between the exercises or the fatigue protocol. The warm-up protocol consisted of 5 minutes of jogging at 10km/h on a treadmill, 5 minutes of dynamic stretching, and 5 minutes of activity-specific protocols. A Yo-Yo squat protocol was used to generate neuromuscular fatigue, based on previous research (Lesinski et al., 2016). The athletes performed Yo-Yo squats, reaching a 90º knee flexion, until they could not maintain a cadence of 70 beats per minute. They performed as many sets as needed until they could not achieve 60% of the repetitions of the first set, with a 1-minute rest between sets. The participants estimated their perceived exertion after each set using a 6-20 Borg Scale to ensure a high level of effort. During the sessions, environmental characteristics were controlled (mean temperature: 21.50º ± 2.17º, mean humidity: 48.40% ± 10.15%), and the athletes drank water ad libitum.

Caffeine ingestion protocol

In this study, the CON (i.e., no substances consumed), CAFF, and PLA sessions were compared. The format and presentation of PLA and CAFF ingestion protocols were identical. The two conditions involved the oral ingestion of 3 opaque capsules with 200ml of water. Participants consumed 6mg/kg of anhydrous CAFF powder (Harrison Sport Nutrition, Granada, Spain) 60 minutes before exercise, as generally recommended (Maughan et al., 2018), whereas PLA consisted of cellulose (Guinama, Valencia, Spain). CAFF dosage calculations were based on participants' body mass during the enrolment session. Both substances were manually encapsulated (Guinama, Valencia, Spain), and researchers ensured that the athletes consumed the capsules.

Blinding

A random allocation sequence was created by a researcher external to the study using a list of computer-generated random numbers (http://www.randomizer.org), to perform fixed simple randomization without restrictions. To implement the random allocation sequence, the researcher enrolling the participants, who was also present during the rest of the sessions, codified their names in the order in which they were enrolled. This codified data was then sent to the same external researcher, who randomly shuffled its order with a web page (https://www.random.org), and related the randomized order of the participants to the simple randomization sequence of numbers (e.g., first athlete and the first number), and the participants were assigned to a group accordingly (e.g., even numbers - CAFF-PLA sequence; odd numbers - PLA-CAFF sequence). The external researcher saved a copy of the allocation list in a location inaccessible to the other investigators. Half of the 14 participants were assigned to each group (allocation ratio 1:1). Afterward, the external researcher placed the opaque capsules of CAFF and PLA in envelopes, and on their outside part, the codified athlete's name and the session in which they were to be consumed were written. Therefore, the participants and all researchers directly involved in the sessions, data collection and analysis, and outcome assessment, were blinded. The treatment order was revealed after the data analyses and outcome adjudication were completed.

Caffeine identification and side effects

Participants completed an online questionnaire during the CAFF and PLA sessions, in which they reported what they believed they had ingested: immediately before and after the assessed exercises, the athletes selected between the options "*caffeine*", "*placebo*", or "*I don't know*", providing a reason for their answer (Saunders et al., 2017). The morning after these sessions, participants completed another online questionnaire comprised of 8 questions with yes/no answers to evaluate the side effects of CAFF during the hours after the sessions (Muñoz et al., 2020), in which the attribution of events was based on the participant's self-perception. These outcomes were compared between the PLA and CAFF sessions and considered secondary.

Statistical analysis

For the analysis of the impact of CAFF on technique and performance, the normal distribution of the non-standardized residuals for each variable was assessed using the Shapiro-Wilk test and Q-Q plots, and any outliers were numerically identified. Since all the variables did not have a normal distribution or had outliers, they were analysed non-parametrically. Data are reported as their median and 25-75 centile range (IQR). An Aligned Rank Transform (ART) ANOVA (Wobbrock et al., 2011) was performed for each outcome to assess the disparities between conditions. If any significant differences were found, post-hoc pairwise comparisons were performed with Bonferroni's correction, using the ART-C procedure (Elkin et al., 2021). The relative ES of the ANOVAs was measured using the partial eta squared (η_p^2) and interpreted as small (0.01), medium (0.06), and large (0.14). For the multiple pairwise comparisons, the adjusted simple ES (differences in means of the aligned ranks) and their 95% confidence interval (CI) are reported. In addition, Cohen's D ES is also reported, interpreted as trivial (<0.2), small (0.2-<0.6), moderate (0.6-<1.2), large (1.2-<2.0), very large (2.0-<4.0), and extremely large (≥4). The ES from ART and ART-C are based on the aligned rank-transformed data, so they should be considered cautiously. *P*-value significance was set at .05.

The effectiveness of blinding was measured using the Bang blinding index (BBI) and reported as the estimate and its 95% CI, as well as the number of cases for each circumstance. The McNemar test was used to assess the differences in the frequencies of side effects using its p-value, and the number of cases is reported descriptively too, but ES and their CI were not calculated due to low or null cases in most variables. The ICC(2,1) was measured (two-way mixed effects, absolute agreement, single rater) to assess the reliability of the 2D analysis variables and was interpreted with the 95% CI as poor (<0.50), moderate (0.50-<0.75), good (0.75-0.90), or excellent (>0.90).

All the analyses considered the data at the outcome time point of the 14 participants who completed the study, as randomized. They were performed using R (v. 4.4.2, R Foundation for Statistical Computing, Vienna, Austria) through RStudio (v. 2023.06.0+421, Posit Software, Boston, United States of America) and the add-on packages "*readxl*", "*dplyr*", "*knitr*", "*rstatix*", "*afex*", "*emmeans*", "*effectsize*", "*car*", "*ARTool*", "*BI*", "*rcompanion*", and "*psych*".

RESULTS

Effect of caffeine on technique and performance

The complete data of the analysed performance and biomechanical outcomes can be found in Supplementary Material 2. Table 2 provides a summary of the significant results from the analyses. Figures 4 and 5 also illustrate some of the main findings.

Table 2. Significant results found in the ART ANOVA and the post-hoc comparisons.

Outcome	ART Anova significant results (*p*-value)	Significant post-hoc comparisons (*p*-value)	Effect direction
Knee angle at midstance	Fatigue (p = .0010)	PRE – POST (p = .0010)	↑ knee angle (e.g., ↓ knee flexion) in POST
Contact time of the right leg	Treatment (p = .0016)	PLA – CON (p = .0010)	↑ contact time in PLA
Contact time of the left leg	Treatment (p = .0212)	PLA – CON (p = .0341)	↑ contact time in PLA
Flight time of the right leg	Fatigue (p = .0002)	PRE – POST (p = .0002)	↓ flight time in POST
Flight time of the left leg	Fatigue (p = .0002)	PRE – POST (p = .0002)	↓ flight time in POST
Step rate of the right leg	Treatment (p = .0060) Fatigue (p = .0070)	CAFF – CON (p = .0057) PRE – POST (p = .0070)	↓ step rate in CAFF ↑ step rate in POST
Step rate of the left leg	Treatment (p = .0069) Fatigue (p = .0057)	CAFF – CON (p = .0069) PRE – POST (p = .0057)	↓ step rate in CAFF ↑ step rate in POST

Stride length of the right leg	Treatment (p = .0065) Fatigue (p = .0055)	CAFF – CON (p = .0058) PRE – POST (p = .0055)	↑ stride length in CAFF ↓ stride length in POST
Stride length of the left leg	Treatment (p = .0094) Fatigue (p = .0071)	CAFF – CON (p = .0091) PRE – POST (p = .0071)	↑ stride length in CAFF ↓ stride length in POST
Running performance	Treatment (p = .0003)	PLA – CON (p = .0011) CAFF – CON (p = .0011)	PLA ↓ time than CON CAFF ↓ time than CON
	Fatigue (p = .0015)	PRE – POST (p = .0015)	↓ time in PRE
	Treatment × Fatigue (p = .0089)	CAFF PRE - PLA POST (p = .0413) PLA PRE - CON POST (p = .0027) PLA PRE - CON PRE (p = .0026) PLA PRE - CAFF POST (p = .0380) CAFF PRE - CON POST (p = .0001) CAFF PRE - CON PRE (p = .0001) CAFF PRE - CAFF POST (p = .0011)	CAFF PRE ↓ time than PLA POST PLA PRE ↓ time than CON POST PLA PRE ↓ time than CON PRE PLA PRE ↓ time than CAFF POST CAFF PRE ↓ time than CON POST CAFF PRE ↓ time than CON PRE CAFF PRE ↓ time than CAFF POST

Note. Abbreviations: PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. ↑= More. ↓= Less.

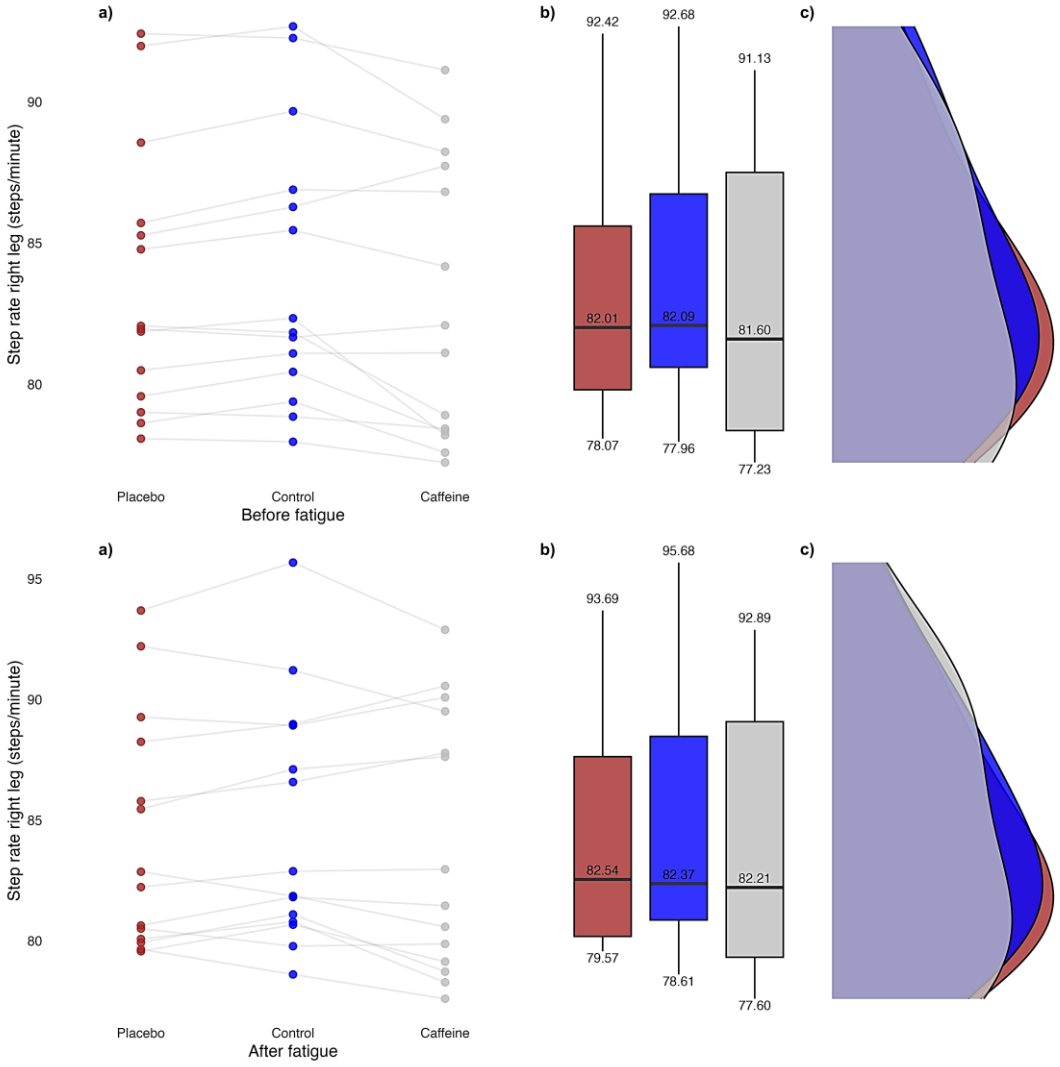

Figure 4. Differences in the step rate of the right leg between the caffeine, control, and placebo sessions, before (top) and after (bottom) the fatiguing protocol. The data for the left leg is not presented due to the similarity in both legs' results. a) Individual data of each participant. b) Box and whisker plot. c) Distribution plot.

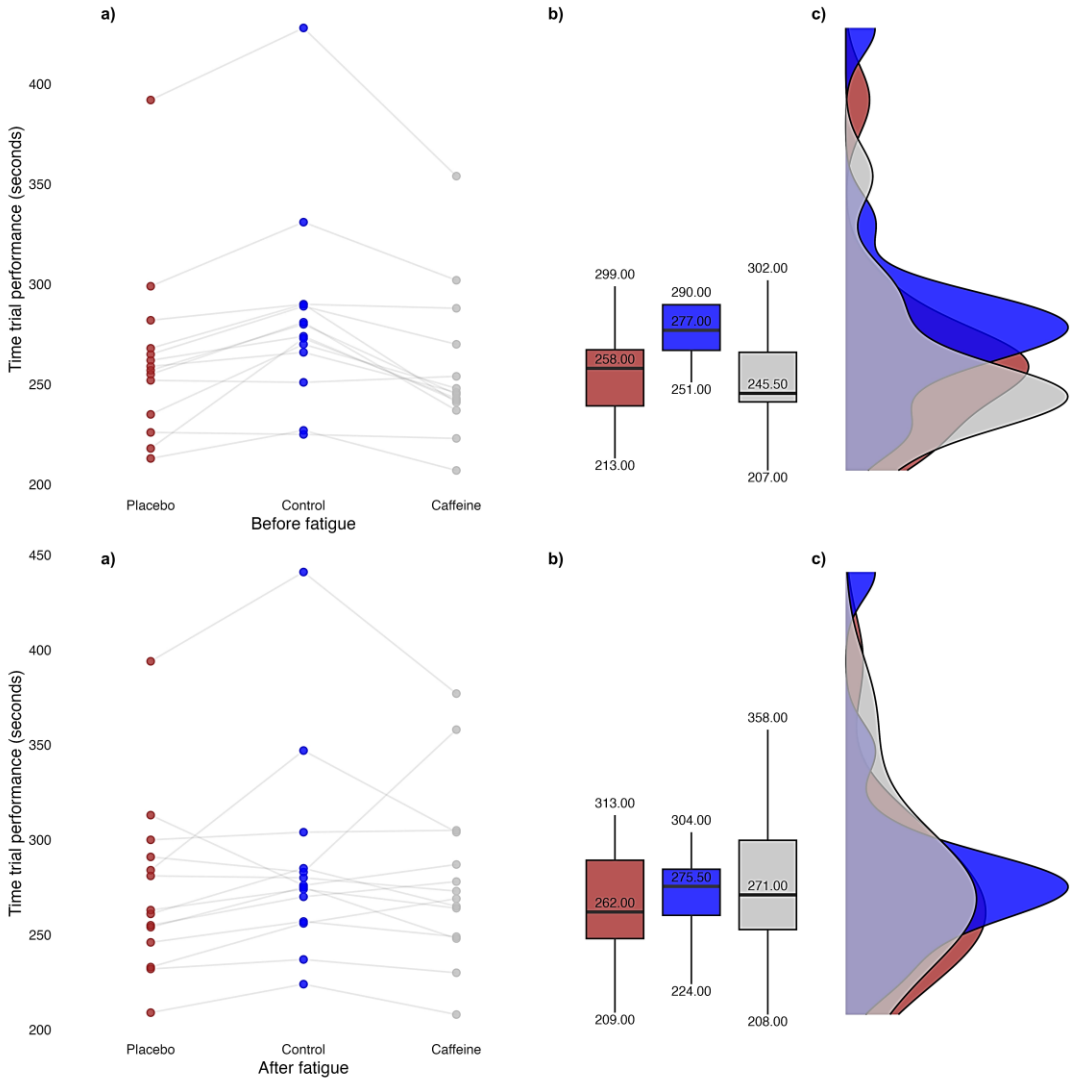

Figure 5. Differences in the running performance between the caffeine, control, and placebo sessions, before (top) and after (bottom) the fatiguing protocol. a) Individual data of each participant. b) Box and whisker plot. c) Distribution plot.

On the other hand, for the tibial angle at midstance, in the ART ANOVA, only a tendency towards significance was found for Treatment (p = .0835) and Fatigue (p = .0513). Likewise, for the flight time of the right leg, only a tendency towards significance was also found for Treatment (p = .0723).

Blinding effectiveness, side effects, and reliability

The complete data of the analysed outcomes for the blinding, side effects, and reliability can be found in Supplementary Material 2. Regarding blinding, when answering before the beginning of the exercises, in the CAFF session, 4/14 participants identified CAFF (BBI = 0.07 [95%CI: -0.30, 0.44]), while in the PLA session, 6/14 athletes identified PLA (BBI = 0.36 [95%CI: 0.04, 0.68]). When answering after the end of the exercises, in the CAFF session, 4/14 athletes identified CAFF (BBI = 0.00 [95%CI: -0.40, 0.40]), while in the PLA session, 4/14 participants identified PLA (BBI = -0.14 [95%CI: -0.58, 0.29]). On the other hand, there were no significant differences in the frequencies of side effects between treatments. Finally, all the 2D variables

showed good to excellent intratester reliability (ICC: 0.91-0.95), except for the knee angle and the tibial angle, for which it was excellent (ICC: 0.97-0.98).

DISCUSSION

The primary objective of this study was to evaluate the impact of CAFF on technique and performance during treadmill running. The results of the trial indicate that: 1) CAFF and PLA reduced the time to complete the time trial, while fatigue had the opposite effect; 2) CAFF, PLA, and fatigue modified the kinematics of running. The impact of some of these effects will be discussed regarding their influence on injury risk and running economy. Because no direct measurements were undertaken for this purpose, this analysis is intended to provide a foundation for future longitudinal and more specific research to determine if these modifications truly have an effect on injuries and running economy. Consequently, no firm conclusions can be drawn in this regard from our results.

Regarding running performance: CAFF without fatigue (PRE) was faster than CAFF with fatigue (POST), PLA POST, CON PRE, and CON POST; PLA PRE was faster than CAFF POST, CON PRE, and CON POST; CAFF was faster than CON; PLA was faster than CON; and PRE was faster than POST. CAFF may enhance running performance (Schubert & Astorino, 2013; Wang et al., 2023) and might modify pacing strategies (Wang et al., 2023). Our results support the performance-enhancing effect of CAFF in time trials, particularly before fatigue and compared to the CON session. They also suggest that CAFF generates a more front-loaded strategy in the effort distribution of exercises with incomplete resting bouts, influenced by the accumulation of fatigue. However, in continuous efforts, this theory may not apply (Rohloff et al., 2022).

It is important to note that PLA performance was also improved. The impression that CAFF has been ingested when knowing its benefits could lead to an improvement in performance (Saunders et al., 2017). Moreover, the belief of having ingested CAFF has been reported to improve performance and affect the pacing (Hurst et al., 2019; Rohloff et al., 2022), and to increase the distance covered while running for a limited time (Valero et al., 2024). Consequently, the CON session is a relevant element to be included in CAFF studies.

As for the biomechanical outcomes, after the fatiguing protocol, there was less knee flexion at midstance. An increased knee range of movement during the stance phase of running has been associated with fatigued conditions (Encarnación-Martínez et al., 2021), and it is unclear whether a larger knee flexion at midstance might enlarge or reduce energetic cost (Van Hooren et al., 2024). In this regard, greater knee flexion during the midstance reduces vertical ground reaction forces and injury risk in the lower extremity, although it could also augment the metabolic cost (Encarnación-Martínez et al., 2021). Besides, both a smaller peak knee flexion angle (Ceyssens et al., 2019) and a more flexed knee in the midstance (Skypala et al., 2023) may be associated with an increased risk of running-related injuries. Therefore, fatigue generated an unexpected strategy that may be energetically efficient, at the expense of more injury risk. However, previous evidence is conflicting in this regard.

On the other hand, PLA generated greater contact time than CON for both legs. Unlike our results, in central fatigue conditions, stance time may be augmented (Encarnación-Martínez et al., 2021), PLA might not be able to modify contact time compared to CON (Valero et al., 2024), and CAFF consumption could decrease support time while sprinting (Horiuchi & Nagahara, 2024). These disparities could be due to differences in the running protocols. Shorter (Ceyssens et al., 2019) and longer (Willwacher et al., 2022) ground contact times have been associated with an increased risk of running-related injuries. Therefore, PLA increased contact time, which has an equivocal impact on injury risk.

Regarding flight time, in the fatigued state, it was reduced in both legs. As in our study, CAFF consumption did not affect flight time during sprints (Horiuchi & Nagahara, 2024). In this regard, it has been hypothesized that a higher duty factor (e.g., shorter contact time and/or longer flight time) could lead to lower energy cost at slower speeds (Van Hooren et al., 2024), such as that analysed in this study. Consequently, PLA and fatigue may be detrimental to the running economy due to their impact on contact time and flight time, respectively.

We also found a lower step rate in CAFF than in CON and a higher step rate in the fatigued state in both legs. In contrast, a sustained stride frequency has been suggested in fatigue conditions, as long as the running speed remains constant (Encarnación-Martínez et al., 2021). PLA has already been shown not to affect step frequency compared to CON (Valero et al., 2024), while CAFF was unable to modify this variable on 100-meter sprints (Matsumura et al., 2023), but increased it during 60-meter sprints (Horiuchi & Nagahara, 2024). A lower step frequency could increase the risk of running-related injuries (Ceyssens et al., 2019; Mesquita et al., 2025). Additionally, deviating too much from the preferred step frequency may reduce running economy (Bernans et al., 2023), and a higher stride frequency has been associated with a lower energetic cost (Van Hooren et al., 2024). Considering this information, CAFF may increase injury risk by lowering the step rate, while fatigue could have the opposite effect. Besides, CAFF may worsen the running economy.

In addition, both legs showed a greater stride length in CAFF than in CON and a shorter stride length in the fatigued state. Contrary to our study, CAFF was not able to modify this variable during sprints (Horiuchi & Nagahara, 2024; Matsumura et al., 2023), and in fatigued conditions with a constant running speed, a sustained stride length can be expected (Encarnación-Martínez et al., 2021). Since a longer stride length when running at a constant speed may lead to a greater energetic cost of running (Van Hooren et al., 2024), CAFF may lower the running economy, while fatigue may increase it.

Considering these results, our hypothesis is partly confirmed, as CAFF was able to modify some aspects of running technique, although its effects were not beneficial for injury risk or running economy. Future research should continue to assess the impact of sports supplements on technique and performance. It would also be interesting to test it using different systems and circumstances closer to competition movements.

Finally, the blinding was better for CAFF than PLA. In the PLA sessions, almost half of the participants correctly identified PLA before exercise, while the same proportion of participants believed that they had consumed CAFF after the session. This may be due to the more stable performance in PLA sessions. Regarding side effects, although no significant differences were found between CAFF and PLA, insomnia, gastrointestinal problems, and tachycardia or palpitations were only reported with CAFF, and there were no cases of irritability overall. Both CAFF and PLA reported the same number of cases of increased activeness and headache, while for the rest of the side effects, CAFF generated a greater incidence.

Limitations

Despite the familiarization session and the easily identifiable session in which no treatment was administered, the difference between CON measures and the two treatments may be biased, as the CON session was always the first to be assessed. However, since 7 athletes underwent the CAFF-PLA and the PLA-CAFF sequence, respectively, the bias effect may be distributed among both treatments. Additionally, similar situations have happened previously (Filip-Stachnik et al., 2022; Horiuchi & Nagahara, 2024; Hurst et al., 2019). Moreover, any carry-over effect of CAFF was likely neglected due to the time between sessions. On the other hand, it is preferable for a randomized controlled trial to have a limited number of primary outcomes (Hopewell et al., 2025). However, due to the nature of this study and its novelty, we believed it may be

interesting to assess diverse variables as primary outcomes. Another limitation is that no sex-specific analyses were performed due to the low number of women participating in this study; nevertheless, these analyses may not be critical, given that CAFF appears to affect both sexes similarly (Montalvo-Alonso et al., 2024; Papadakis et al., 2025). Finally, the reported results should be interpreted with caution when attempting to extrapolate them beyond the circumstances of this trial.

CONCLUSIONS

CAFF improved performance in running time trials compared to CON, suggesting a front-loaded strategy in efforts with an incomplete rest. PLA also enhanced performance relative to CON, which highlights the importance of including CON sessions in ergogenic aids research. Furthermore, CAFF, PLA, and fatigue were able to modify the kinematics of running, adding another layer of complexity when assessing the appropriateness of CAFF ingestion for each athlete.

AUTHOR CONTRIBUTIONS

ABR: conceptualization, methodology, validation, formal analysis, investigation, resources, data curation, writing – original draft, visualization, supervision, project administration, funding acquisition. XBB: conceptualization, methodology, validation, formal analysis, investigation, resources, writing – review & editing, visualization, supervision. JP: conceptualization, methodology, validation, formal analysis, investigation, writing – review & editing, visualization, supervision, funding acquisition.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in CORA.RDR repository at https://doi.org/10.34810/data2401.

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SUPPLEMENTARY MATERIAL 1: CONSORT checklist.

Table 1. CONSORT 2025 checklist item description, adapted using the CONSORT 2010 extension to randomized crossover trials (Dwan et al., 2019; Hopewell et al., 2025).

Section/topic	No	CONSORT 2025 checklist item description, adapted using the CONSORT 2010 extension to randomized crossover trials	Reported on
Title and abstract			
Title and structured abstract	1a	Identification as a randomized crossover trial	Title
	1b	Structured summary of the trial design, methods, results, and conclusions	Abstract
Open science			
Trial registration	2	Name of trial registry, identifying number (with URL) and date of registration	Study design
Protocol and statistical analysis plan	3	Where the trial protocol and statistical analysis plan can be accessed	Study design
Data sharing	4	Where and how the individual de-identified participant data (including data dictionary), statistical code and any other materials can be accessed	Data availability statement
Funding and conflicts of interest	5a	Sources of funding and other support (e.g., supply of drugs), and role of funders in the design, conduct, analysis and reporting of the trial	Supporting agencies
	5b	Financial and other conflicts of interest of the manuscript authors	Disclosure statement
Introduction			
Background and rationale	6	Scientific background and rationale	Introduction / Discussion
Objectives	7	Specific objectives related to benefits and harms	Introduction
Methods			
Patient and public involvement	8	Details of patient or public involvement in the design, conduct and reporting of the trial	Study design
Trial design	9	Rationale for a crossover design. Description of trial design including type of trial (e.g., parallel group, crossover), allocation ratio, the number and duration of periods, duration of wash-out period, consideration of carry over effect, and framework (e.g., superiority, equivalence, non-inferiority, exploratory)	Study design / Blinding
Changes to trial protocol	10	Important changes to the trial after it commenced including any outcomes or analyses that were not prespecified, with reason	Study design
Trial setting	11	Settings (e.g., community, hospital) and locations (e.g., countries, sites) where the trial was conducted	Participants / Study design
Eligibility criteria	12a	Eligibility criteria for participants	Participants / Study design
	12b	If applicable, eligibility criteria for sites and for individuals delivering the interventions (e.g., surgeons, physiotherapists)	Not applicable
Intervention and comparator	13	Intervention and comparator with sufficient details to allow replication, including how and when they were actually administered. If relevant, where additional materials describing the intervention and comparator (e.g., intervention manual) can be accessed	Caffeine ingestion protocol
Outcomes	14	Prespecified primary and secondary outcomes, including the specific measurement variable (e.g., systolic blood pressure), analysis metric (e.g., change from baseline, final value, time to event), method of aggregation (e.g., median, proportion), and time point for each outcome	Introduction / Caffeine identification and side effects / Measures
Harms	15	How harms were defined and assessed (e.g., systematically, non-systematically)	Caffeine identification and side effects
Sample size	16a	How sample size was determined, accounting for within participant variability and including all assumptions supporting the sample size calculation	Participants

Randomization:	16b	Explanation of any interim analyses and stopping guidelines	Study design
Sequence generation	17a	Who generated the random allocation sequence and the method used	Blinding
	17b	Type of randomization and details of any restriction (e.g., stratification, blocking and block size)	Blinding
Allocation concealment mechanism	18	Mechanism used to implement the random allocation sequence (e.g., central computer/telephone; sequentially numbered, opaque, sealed containers), describing any steps to conceal the sequence until interventions were assigned	Blinding
Implementation	19	Whether the personnel who enrolled and those who assigned participants to the interventions had access to the random allocation sequence. Who generated the random allocation sequence, who enrolled participants, and who assigned participants to the sequence of interventions	Blinding
Blinding	20a	Who was blinded after assignment to interventions (e.g., participants, care providers, outcome assessors, data analysts)	Blinding
	20b	If blinded, how blinding was achieved and description of the similarity of interventions	Caffeine ingestion protocol
Statistical methods	21a	Statistical methods used to compare groups for primary and secondary outcomes, including harms, which are appropriate for crossover design (that is, based on within participant comparison)	Statistical analysis
	21b	Definition of who is included in each analysis (e.g., all randomized participants), and in which group	Statistical analysis
	21c	How missing data were handled in the analysis	Not applicable
	21d	Methods for any additional analyses (e.g., subgroup and sensitivity analyses), distinguishing prespecified from post hoc	Not applicable
Results			
Participant flow, including flow diagram	22a	The numbers of participants who were randomly assigned, received intended treatment, and were analysed for the primary outcome, separately for each sequence and period	Participants
	22b	Number of participants excluded at each stage, with reasons, separately for each sequence and period	Participants
Recruitment	23a	Dates defining the periods of recruitment and follow-up for outcomes of benefits and harms	Participants/Study design
	23b	If relevant, why the trial ended or was stopped	Not applicable
Intervention and comparator delivery	24a	Intervention and comparator as they were actually administered (e.g., where appropriate, who delivered the intervention/comparator, how participants adhered, whether they were delivered as intended (fidelity))	Caffeine ingestion protocol / Statistical analysis
	24b	Concomitant care received during the trial for each group	Not applicable
Baseline data	25	A table showing baseline demographic and clinical characteristics by sequence and period	Participants
Numbers analysed, outcomes and estimation	26	For each primary and secondary outcome, based on within participant comparisons: ● Number of participants (denominator) included in each analysis and whether the analysis was by original assigned groups ● the number of participants with available data at the outcome time point ● result for each group, and the estimated effect size and its precision (such as 95% confidence interval). In addition, results for each intervention in each period are recommended ● for binary outcomes, presentation of both absolute and relative effect size	Statistical analysis / Results / Supplementary material
Harms	27	Describe all important harms or untended effects in a way that accounts for the design	Results / Supplementary material
Ancillary analyses	28	Any other analyses performed, including subgroup and sensitivity analyses, distinguishing pre-specified from post hoc	Not applicable
Discussion			
Interpretation	29	Interpretation consistent with results, balancing benefits and harms, and considering other relevant evidence	Discussion
Limitations	30	Trial limitations, addressing sources of potential bias, imprecision, generalizability, and, if relevant, multiplicity of analyses. Consider potential carry over effects	Limitations

SUPPLEMENTARY MATERIAL 2: Participants' outcome results.

MAIN ANALYSES

Table 1. Results of the statistical analyses of the knee angle at midstance.

ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.1244	0.06 $F_{(2,65)}$ = 2.1528	[0.00, 0.16]
Fatigue	.0010*	0.15 $F_{(1,65)}$ = 11.8172	[0.04, 0.29]
Treatment*Fatigue	.9334	2.12e-03 $F_{(2,65)}$ = 0.0690	[0.00, 0.01]

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0010*	7.33	[3.07, 11.6]	0.75
Pre			Post	
Median	IQR		Median	IQR
130.19º	128.31º-132.94º		131.70º	129.22º-134.37º

*Note. Abbreviations: PRE = Values before fatigue. POST = Values after fatigue. ηp2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05.*

Table 2. Results of the statistical analyses of the tibial angle at midstance.

ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0835^	0.07 $F_{(2,65)}$ = 2.5809	[0.00, 0.18]
Fatigue	.0513^	0.06 $F_{(1,65)}$ = 3.9434	[0.00, 0.17]
Treatment*Fatigue	.6571	0.01 $F_{(2,65)}$ = 0.4227	[0.00, 0.07]

PAIR-WISE COMPARISON

Treatment					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	.4552	4.46	[-3.10, 12.03]		0.39
PLA-CAFF	.0856^	6.89	[-0.67, 14.46]		0.60
CON-CAFF	1.0000	2.43	[-5.14, 9.99]		0.21
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
28.24º	25.97º-30.68º	27.18º	25.90º-29.89º	27.70º	25.26º-29.36º

PAIR-WISE COMPARISON

Fatigue				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0513^	-5.00	[-10.00, 0.03]	-0.43
Pre			Post	
Median	IQR		Median	IQR
28.42º	26.05º-30.51º		27.24º	25.32º-29.94º

Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. ^ Denotes p = >.05 - <.10.

Table 3. Results of the statistical analyses of the contact time of the right leg.
ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0016*	0.18 $F_{(2,65)}$ = 7.1485	[0.05, 0.31]
Fatigue	.1415	0.03 $F_{(1,65)}$ = 2.2150	[0.00, 0.13]
Treatment*Fatigue	.9538	1.46e-03 $F_{(2,65)}$ = 0.0474	[0.00, 0.00]

PAIR-WISE COMPARISON

Treatment					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	.0010*	8.93	[3.12, 14.73]		1.01
PLA-CAFF	.2299	4.25	[-1.56, 10.06]		0.48
CON-CAFF	.1556	-4.68	[-10.48, 1.13]		-0.53
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
0.287s	0.269s-0.304s	0.281s	0.266s-0.290s	0.284s	0.265s-0.304s

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05.*

Table 4. Results of the statistical analyses of the contact time of the left leg.
ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0212*	0.11 $F_{(2,65)}$ = 4.093	[0.01, 0.23]
Fatigue	.1231	0.04 $F_{(1,65)}$ = 2.441	[0.00, 0.14]
Treatment*Fatigue	.5135	0.02 $F_{(2,65)}$ = 0.6733	[0.00, 0.09]

PAIR-WISE COMPARISON

Treatment					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	.0341*	6.00	[0.34, 11.66]		0.70
PLA-CAFF	1.0000	0.64	[-5.02, 6.30]		0.08
CON-CAFF	.0694^	-5.36	[-11.02, 0.30]		-0.62
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
0.282s	0.263s-0.297s	0.276s	0.253s-0.287s	0.280s	0.256s-0.299s

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

Table 5. Results of the statistical analyses of the flight time of the right leg.
ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0723^	0.08 $F_{(2,65)}$ = 2.7359	[0.00, 0.19]
Fatigue	.0002*	0.19 $F_{(1,65)}$ = 15.0618	[0.07, 0.33]
Treatment*Fatigue	.7026	0.01 $F_{(2,65)}$ = 0.3549	[0.00, 0.06]

PAIR-WISE COMPARISON

Treatment					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	1.0000	-1.75	[-6.60, 3.10]		-0.24
PLA-CAFF	.0708^	-4.57	[-9.42, 0.28]		-0.62
CON-CAFF	.4719	-2.82	[-7.67, 2.03]		-0.38
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
0.422s	0.390s-0.467s	0.425s	0.394s-0.469s	0.413s	0.393s-0.487s

PAIR-WISE COMPARISON

Fatigue				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0002*	-6.14	[-9.30, -2.98]	-0.85
Pre			Post	
Median	IQR		Median	IQR
0.426s	0.398s-0.477s		0.410s	0.383s-0.473s

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

Table 6. Results of the statistical analyses of the flight time of the left leg.

ART ANOVA

Effect	***p*-Value**	**η_p^2**	**90%CI η_p^2**
Treatment	.1017	0.07 $F_{(2,65)}$ = 2.3676	[0.00, 0.17]
Fatigue	.0002*	0.19 $F_{(1,65)}$ = 15.3215	[0.07, 0.33]
Treatment*Fatigue	.9512	1.54e-03 $F_{(2,65)}$ = 0.0500	[0.00, 0.00]

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	0.0002*	-6.43	[-9.71, -3.15]	-0.85
Pre			Post	
Median	IQR		Median	IQR
0.429s	0.402s-0.491s		0.415s	0.388s-0.489s

*Note. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05.*

Table 7. Results of the statistical analyses of the step rate of the right leg.

ART ANOVA

Effect	***p*-Value**	**η_p^2**	**90%CI η_p^2**
Treatment	.0060*	0.15 $F_{(2,65)}$ = 5.5346	[0.03, 0.27]
Fatigue	.0070*	0.11 $F_{(1,65)}$ = 7.7697	[0.02, 0.24]
Treatment*Fatigue	.6796	0.01 $F_{(2,65)}$ = 0.3886	[0.00, 0.06]

PAIR-WISE COMPARISON

TREATMENT					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	1.0000	-2.04	[-7.33, 3.25]		-0.25
PLA-CAFF	.0759^	4.93	[-0.36, 10.22]		0.61
CON-CAFF	.0057*	6.96	[1.67, 12.25]		0.86
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
82.15 steps/min	80.04 steps/min-86.40 steps/min	82.10 steps/min	80.76 steps/min-87.56 steps/min	81.77 steps/min	78.65 steps/min-87.90 steps/min

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0070*	4.81	[1.36, 8.26]	0.61
Pre			Post	
Median	IQR		Median	IQR
82.01 steps/min	79.10 steps/min-86.87 steps/min		82.54 steps/min	80.18 steps/min-88.76 steps/min

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

Table 8. Results of the statistical analyses of the step rate of the left leg.

ART ANOVA

Effect	***p*-Value**	**η_p^2**	**90%CI η_p^2**
Treatment	.0069*	0.14 $F_{(2,65)}$ = 5.3718	[0.03, 0.27]
Fatigue	.0057*	0.11 $F_{(1,65)}$ = 8.1630	[0.02, 0.24]
Treatment*Fatigue	.6477	0.01 $F_{(2,65)}$ = 0.4373	[0.00, 0.07]

PAIR-WISE COMPARISON

TREATMENT					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	1.0000	-1.89	[-7.23, 3.45]		-0.23
PLA-CAFF	.0738^	5.00	[-0.34, 10.34]		0.62
CON-CAFF	.0069*	6.89	[1.55, 12.23]		0.85
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
82.26 steps/min	80.07 steps/min-86.45 steps/min	82.08 steps/min	80.83 steps/min-87.51 steps/min	81.85 steps/min	78.65 steps/min-87.94 steps/min

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0057*	4.9	[1.48, 8.33]	0.62
Pre			Post	
Median	IQR		Median	IQR
82.09 steps/min	79.15 steps/min-87.06 steps/min		82.55 steps/min	80.21 steps/min-88.53 steps/min

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

Table 9. Results of the statistical analyses of the stride length of the right leg.

ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0065*	0.14 $F_{(2,65)}$ = 5.4526	[0.03, 0.27]
Fatigue	.0055*	0.11 $F_{(1,65)}$ = 8.2627	[0.02, 0.24]
Treatment*Fatigue	.6777	0.01 $F_{(2,65)}$ = 0.3915	[0.00, 0.07]

PAIR-WISE COMPARISON

TREATMENT					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	.9412	2.18	[-3.09, 7.45]		0.27
PLA-CAFF	.0911^	-4.75	[-10.02, 0.52]		-0.59
CON-CAFF	.0058*	-6.93	[-12.20, -1.66]		-0.86
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
2.13m	2.03m-2.19m	2.13m	2.00m-2.17m	2.14m	1.99m-2.23m

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0055*	-4.95	[-8.39, -1.51]	-0.63
Pre			Post	
Median	IQR		Median	IQR
2.13m	2.01m-2.21m		2.12m	1.97m-2.18m

Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 *= Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

Table 10. Results of the statistical analyses of the stride length of the left leg.

ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0094*	0.13 $F_{(2,65)}$ = 5.0195	[0.02, 0.26]
Fatigue	.0071*	0.11 $F_{(1,65)}$ = 7.7257	[0.02, 0.23]
Treatment*Fatigue	.6507	0.01 $F_{(2,65)}$ = 0.4326	[0.00, 0.07]

PAIR-WISE COMPARISON

TREATMENT					
Effect	***p*-Value**	**Simple effect size (Estimate)**	**95%CI Simple effect size (lower CL, upper CL)**		**Cohen's D**
PLA-CON	1.0000	1.96	[-3.39, 7.32]		0.24
PLA-CAFF	.0987^	-4.75	[-10.11, 0.61]		-0.58
CON-CAFF	.0091*	-6.71	[-12.07, -1.36]		-0.82
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
2.13m	2.02m-2.19m	2.13m	2.00m-2.17m	2.14m	1.99m-2.23m

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0071*	-4.81	[-8.27, -1.35]	-0.61
Pre			Post	
Median	IQR		Median	IQR
2.13m	2.01m-2.21m		2.12m	1.98m-2.18m

Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 *= Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05. ^ Denotes p = >.05 - <.10.*

Table 11. Results of the statistical analyses of the running performance.

ART ANOVA

Effect	*p*-Value	η_p^2	90%CI η_p^2
Treatment	.0003*	0.22 $F_{(2,65)}$ = 9.4208	[0.08, 0.36]
Fatigue	.0015*	0.14 $F_{(1,65)}$ = 10.9809	[0.04, 0.28]
Treatment*Fatigue	.0089*	0.14 $F_{(2,65)}$ = 5.0888	[0.02, 0.26]

PAIR-WISE COMPARISON

TREATMENT*FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
PLA,Post - PLA,Pre	.7089	7.75	[-3.93, 19.43]	0.76
PLA,Post - CON,Post	.8364	-7.46	[-19.14, 4.21]	-0.74
PLA,Post - CON,Pre	.8195	-7.50	[-19.18, 4.18]	-0.74
PLA,Post - CAFF,Post	1.0000	-4.29	[-15.96, 7.39]	-0.42
PLA,Post - CAFF,Pre	.0413*	11.93	[0.25, 23.61]	1.17
PLA,Pre - CON,Post	.0027*	-15.21	[-26.89, -3.54]	-1.50
PLA,Pre - CON,Pre	.0026*	-15.25	[-26.93, -3.57]	-1.50
PLA,Pre - CAFF,Post	.0380*	-12.04	[-23.71, -0.36]	-1.19
PLA,Pre - CAFF,Pre	1.0000	4.18	[-7.50, 15.86]	0.41
CON,Post - CON,Pre	1.0000	-0.04	[-11.71, 11.64]	-0.01
CON,Post - CAFF,Post	1.0000	3.18	[-8.50, 14.86]	0.31
CON,Post - CAFF,Pre	.0001*	19.39	[7.71, 31.07]	1.91
CON,Pre - CAFF,Post	1.0000	3.21	[-8.46, 14.89]	0.32
CON,Pre - CAFF,Pre	.0001*	19.43	[7.75, 31.11]	1.92
CAFF,Post - CAFF,Pre	.0011*	16.21	[4.54, 27.89]	1.60

PLA PRE		PLA POST	
Median	IQR	Median	IQR
258.00s	239.25s-267.25s	262.00s	248.00s-289.25s
CON PRE		CON POST	
Median	IQR	Median	IQR
277.00s	267.00s-289.75s	275.50s	260.25s-284.50s
CAFF PRE		CAFF POST	
Median	IQR	Median	IQR
245.50s	241.25s-266.00s	271.00s	252.75s-299.75s

PAIR-WISE COMPARISON

TREATMENT					
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**		**Cohen's D**
PLA-CON	.0011*	-11.02	[-18.23, -3.80]		-1.00
PLA-CAFF	1.0000	0.04	[-7.18, 7.25]		0.01
CON-CAFF	.0011*	11.05	[3.84, 18.27]		1.01
PLA		CON		CAFF	
Median	IQR	Median	IQR	Median	IQR
260.00s	243.25s-282.50s	275.50s	263.75s-289.25s	259.00s	242.75s-287.25s

PAIR-WISE COMPARISON

FATIGUE				
Effect	***p*-Value**	**Simple effect size**	**95%CI Simple effect size**	**Cohen's D**
POST-PRE	.0015*	7.95	[3.16, 12.70]	0.72
Pre			Post	
Median	IQR		Median	IQR
260.50s	242.25s-281.75s		273.50s	254.25s-290.00s

*Note. PLA = Placebo session. CON = Control Session. CAFF = Caffeine session. PRE = Values before fatigue. POST = Values after fatigue. η_p^2 = Partial eta squared. CI = Confidence Intervals. IQR = 25-75 centile range. * Denotes p < .05.*

BLINDING EFFECTIVENESS

Table 12. Blinding effectiveness, before and after the assessed exercises.

PRE SESSION		
	CAFF	**PLA**
CAFF Perception	4/14	1/14
PLA Perception	3/14	6/14
I don't know	7/14	7/14

POST SESSION		
	CAFF	**PLA**
CAFF Perception	4/14	6/14
PLA Perception	4/14	4/14
I don't know	6/14	4/14

Note. PLA = Placebo session. CAFF = Caffeine session. PLA PERCEPTION = Placebo perception. CAFF PERCEPTION = Caffeine perception.

SIDE EFFECTS

Table 13. Results of the side effects analyses.

Side effect	**Count in CAFF**	**Count in PLA**	**McNemar's Chi-Squared**	***p*-Value**
Insomnia	4/14	0/14	2.25	.1336
Increased urine production	3/14	1/14	0.25	.6171
Gastrointestinal problems	1/14	0/14	0	1.0000
Increased activeness	4/14	4/14	0	1.0000
Headache	1/14	1/14	0	1.0000
Irritability	0/14	0/14	NaN	NA
Muscular pain	3/14	2/14	0	1.0000
Tachycardia or palpitations	2/14	0/14	0.5	.4795

Note. PLA = Placebo session. CAFF = Caffeine session.

RELIABILITY

Table 14. Reliability of the analysed variables.

Variable	**$ICC_{(2,1)}$**	**95%CI**	**Interpretation**
Knee angle at the midstance (º)	0.97	[0.91,0.99]	Excellent
Tibial angle at the midstance (º)	0.98	[0.93,0.99]	Excellent
Contact time right leg (s)	0.94	[0.85,0.98]	Good to excellent
Contact time left leg (s)	0.95	[0.86,0.99]	Good to excellent
Flight time right leg (s)	0.92	[0.79,0.98]	Good to excellent
Flight time left leg (s)	0.91	[0.78,0.98]	Good to excellent

Note. ICC = Intraclass Correlation Coefficient. CI = Confidence Intervals. º = degrees. s = Seconds.

