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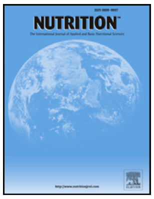

Applied nutritional investigation

Boost or bust? A randomized crossover study on pre-exercise caffeine supplementation for fatigue management in basketball

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ABSTRACT

The aim of this study was to to assess the effect of pre-exercise caffeine intake (CAF) on fatigue and recovery in basketball. Using a randomized crossover design, 14 amateur male players completed two basketball-specific training sessions (in-season phase, February–March 2024), preceded by CAF (3 mg/kg body weight) or placebo ingestion (CON). Countermovement jump height, 10- and 20-m sprint times, heart rate variability (Ln-rMSSD), static and dynamic muscle soreness, and perceived fatigue were recorded at pre-training, post-training and 24 h post-training to evaluate the effectiveness of caffeine supplementation. The results showed no significant differences between CAF and CON at corresponding time points for any variable ($P > 0.05$). Regarding the effect of time, the main findings indicate that countermovement jump (average percentage change [%Δ] = –7% to –10%) and Ln-rMSSD (%Δ = –33% to –54%) decreased at post-training compared with all other time points ($P < 0.001$, effect size = 1.41–1.98), while 10-m sprint times deteriorated from pre-to-post-training ($P = 0.029$, effect size = 0.69, %Δ = –2%). Similarly, muscle soreness (%Δ = +171%) and perceived fatigue (%Δ = +156%) increased from pre-to-post-training in both interventions ($P \leq 0.006$, $r = 0.57$–0.61), with static soreness in CON (%Δ = +127%) and dynamic soreness in CAF (%Δ = +139%) remaining higher than pre-training levels up to 24 h post-training ($P \leq 0.010$, $r = 0.53$–0.58). These findings suggest that pre-exercise caffeine intake did not significantly affect markers of fatigue in amateur basketball players, either acutely or 24 h post-training.

Introduction

Basketball is a team sport of intermittent nature, which relies on the players' ability to repeatedly perform high-intensity activities (e.g., sprints, jumps, accelerations, decelerations) [1]. Due to the considerable physical and physiological demands imposed by basketball activity, coaches employ a variety of interventions during training and competition, in order to maximize players' performance and achieve team success [2–4]. Among these approaches, adequate nutrition and supplementation are essential to aid physical and cognitive performance, promote training adaptations, reduce injury risk [5], and improve players' recovery and well-being [6].

Caffeine is a widely used ergogenic aid, which has been shown to enhance strength, power, and cognitive function, in addition to increasing physical performance during prolonged (i.e., endurance) and high-intensity exercise [7]. Previous research indicates that the primary mechanism by which caffeine improves performance is by antagonizing the action of adenosine in the central nervous system, thereby upregulating the release of several neurotransmitters (e.g., serotonin, dopamine, acetylcholine, norepinephrine, glutamate), which—in turn—increases motor unit firing rates, mood, and alertness [7]. Accordingly, previous review studies [8,9] indicate that caffeine intake appears to have an acute, beneficial effect on jump, sprint, and change-of-direction performance among basketball players.

In addition to performance enhancement, another area that has received increasing attention in recent years is related to the potential effects of caffeine on exercise-induced fatigue [10–12]. Previous reports [13,14] have provided a comprehensive

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characterization of fatigue, which is crucial to identify its effects on performance in competitive sport. Specifically, fatigue has been conceptualized through two interacting components: perceived fatigability and performance fatigability [13]. Perceived fatigability refers to changes in physiological (e.g., muscle damage, inflammation, cardiac parasympathetic activity) and perceptual (e.g., muscle soreness, perceived fatigue) indicators that reflect the body's attempt to maintain balance during or after exercise, while performance fatigability describes the measurable decline in physical performance (e.g., strength/power output, speed) resulting from reduced neural drive or changes in muscle function [13]. Within this framework, fatigue can be described as a reduction in cognitive and/or physical performance that arises from the combined effects of perceived and performance fatigability [13,14]. This characterization is especially important in the present context, as basketball activity has been shown to induce both acute (i.e., measured shortly after exercise) and residual (up to 24–48 h post-exercise) fatigue, assessed through measures of performance (e.g., countermovement jump [CMJ], sprinting), physiological status (e.g., muscle damage, inflammation and cardiac parasympathetic activity) and perceived well-being (e.g., muscle soreness and perceived fatigue) [1]. Therefore, the accessibility of a commercially available supplement like caffeine makes it a potentially convenient option for basketball practitioners seeking to manage fatigue. Interestingly, previous research in other populations [10,11] suggested that caffeine could improve the ability to train and compete under fatigue, thanks to its ergogenic properties and the proposed positive effects on pain (particularly muscle soreness) and the overall perception of fatigue [11]. Moreover, previous research suggests that caffeine may support functional (i.e., performance-related) recovery [15,16], possibly via increased motor unit recruitment and preservation of excitation–contraction coupling dynamics [10,15,17]. Therefore, addressing the effect of caffeine on perceptual (e.g., muscle soreness, perceived fatigue) and performance-related measures of fatigue (especially highly-specific ones, such as jump height and sprint performance [1]) may prove useful to basketball practitioners. However, previous research [18,19] suggested that caffeine may have detrimental effects on other aspects of recovery, as indicated by potential delays in post-exercise parasympathetic reactivation, measured through heart rate variability (HRV). Given that cardiovascular homeostasis plays a crucial role in post-exercise recovery [20], this poses an interesting dilemma when considering the effects of caffeine supplementation on HRV metrics, such as reliable and practically relevant indices like Ln-rMSSD (log-transformed root mean square of successive differences between R-R intervals) [21]. Considering that no basketball-directed study has explored this aspect, research is warranted in this specific context. Finally, it has been previously highlighted that the ergogenic benefits of caffeine—although useful in the acute phase—could result in increased total work performed during exercise, potentially amplifying fatigue during the recovery phase [12].

To the best of our knowledge, no study has directly assessed the effect of caffeine supplementation as a tool to manage fatigue and recovery following a single bout of basketball-specific activity, highlighting the need for research in this area. Indeed, examining interventions in ecologically valid conditions is crucial to ensure the applicability of research findings in a particular sport [22]. Therefore, the aim of this study was to investigate the effect of pre-exercise caffeine intake on performance (CMJ, 10- and 20-m sprint times), physiological (HRV), and perceptual (muscle soreness and perceived fatigue) measures of fatigue following a basketball training session in amateur male players. It was hypothesized that—compared to a placebo—caffeine would limit performance-related fatigue, muscle soreness, and perceived fatigue, while possibly exerting a negative effect on autonomic recovery measured through HRV.

Materials and methods

Design

Prior to the beginning of the study, participants were familiarized with all procedures. Additionally, they were instructed to follow a stable diet (i.e., avoiding excessive daily fluctuations in food intake) and to maintain their usual sleep routines, with periodic reminders provided throughout the study period.

Using a double-blind, randomized, placebo-controlled crossover design (Fig. 1), all participants were involved in two 80-min basketball training sessions, each corresponding to one of two interventions: 1) pre-exercise caffeine supplementation (CAF); 2) pre-exercise placebo ingestion (CON). The two sessions were separated by a 2-wk washout period, with player allocation randomized by researchers not involved in the study (to blind participants and investigators regarding the intervention utilized in each session). Specifically, randomization was performed using a freely available online tool (https://www.randomlists.com/team-generator). For each session, measures of performance (CMJ height, 10- and 20-m sprint times), physiological (HRV), and perceptual fatigue (muscle soreness and perceived fatigue) were assessed at pre-training, post-training, and 24 h post-training. Additionally, external and internal loads were monitored during both sessions.

To avoid potential bias related to variations in fatigue status at baseline (i.e., pre-training) and 24 h post-training, participants were instructed to refrain from physical activity during the 48 h preceding each training session, as well as during the 24 h following each session, until all measurements (i.e., performance, physiological and perceptual assessment) were completed.

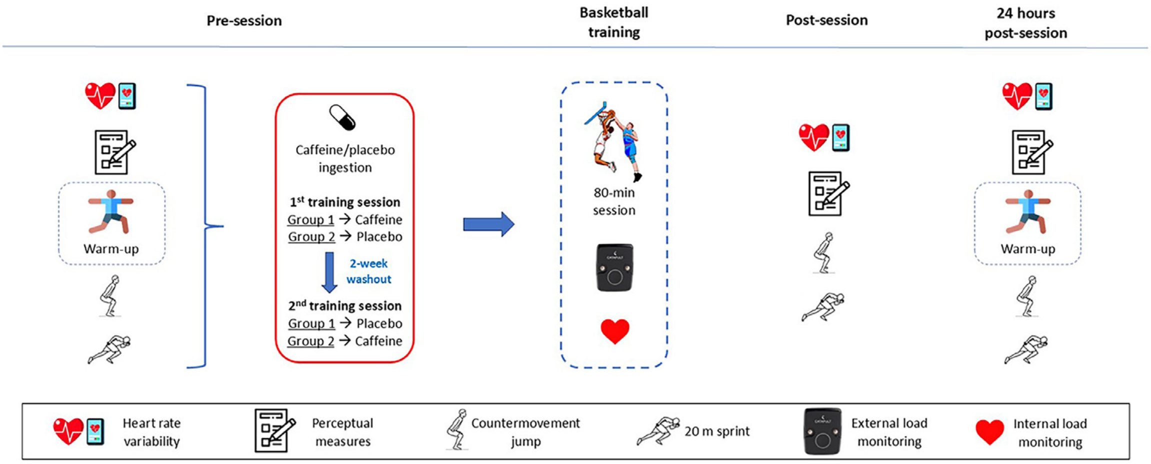

Fig. 1. Study procedures and timeline.

Participants

Seventeen amateur male basketball players were initially recruited for this study. Inclusion criteria comprised the following: 1) players had to be part of their basketball team (i.e., no team transfers or dropouts) for the entire duration of the study, and complete the two basketball-specific training sessions; 2) players had to be injury-free across the experimental period; 3) players had to be free from the following health conditions: severe anxiety, cardiovascular diseases, peptic ulcer disease, gastroesophageal reflux disease, hepatic impairment, renal impairment and seizures [23]. During the study, three players were excluded due to missed participation in either of the two examined training sessions. Therefore, 14 players (age: 20.9 ± 1.5 y, stature: 193.4 ± 7.8 cm, body mass: 84.1 ± 8.3 kg; basketball playing experience: 12.9 ± 1.9 y) were retained for analysis. A priori power analysis (G*Power version 3.1.9.7, University of Düsseldorf, Germany) indicated that this sample size was adequate (minimum $n = 9$) using $\alpha = 0.05$, $\beta = 0.80$, and effect size (ES) = 1.14, based on previous basketball-specific research showing caffeine-induced improvements in 20-m sprint performance [24]. During the study period (in-season phase, February–March 2024), the players' typical weekly schedule included three 90-min basketball-specific training sessions (training volume: 4.5 h/wk) and 1 to 2 competitive matches. After explanation of the experimental design, written consent was gathered from all players. The study was approved by the Lithuanian Sports University Ethics Committee (NR. BNL-TRS (B)-2023-657) and designed according to the Declaration of Helsinki.

Procedures

Basketball training sessions

All players took part in two identically structured 80-min training sessions (i.e., one for each intervention), each following the exact same drill sequence and durations: 1) basketball-specific warm-up (10 min); 2) dynamic stretching (10 min); 3) 2-on-1 and 3-on-2 fast-break drills (10 min); 4) 1-on-1 (10 min) drills; 5) shooting (10 min); 6) 2-on-2 drills (10 min); 7) 5-on-5 drills (20 min).

Caffeine supplementation

Prior to the study period, the habitual caffeine consumption for each participant was determined using a validated Caffeine Consumption Questionnaire [25], yielding a mean ± standard deviation of 1519 ± 1189 mg/wk (see Table S1 in the Supplementary Material for individual information). Participants were also given a comprehensive list of caffeine-containing foods and drinks, and were asked to abstain from these products for a minimum of 36 h before each training session (to allow caffeine wash-out [26]), and until measurements at 24 h post-training were completed.

Body mass was measured (to the nearest 0.1 kg) using an electronic scale (Tanita Body Composition Analyzer BC-545N, Tanita Corporation, Japan). Subsequently, capsules containing ~3 mg/kg body weight of either caffeine (FlorioSport, Casalnuovo di Napoli, Italy) or placebo (i.e., dextrose; Cargill Deutschland GmbH, Krefeld, Germany) were prepared and coded by researchers not involved in the study, to blind participants and investigators regarding the intervention used in each experimental session. To ensure effective blinding, identical double-zero (00) size cellulose capsules were used for both caffeine and placebo. The contents of the capsules matched in color and texture, ensuring uniform appearance. Following data collection, details regarding participant allocation were disclosed to the investigators. Table S2 (Supplementary Material) shows the required (i.e., pre-calculated) caffeine dosage for each participant, along with the actual caffeine content (reflecting the final dosage after capsule preparation). Immediately before the start of each training session, the caffeine/placebo capsules were administered to the participants (see Fig. 1). As a result of the standardized duration of each session (80 min), the time between pre-training supplementation and post-training assessment (i.e., performance, physiological and perceptual outcomes) also remained consistent across interventions.

Performance assessment

Performance assessment at all time points (except for post-training) was conducted following a ~10-min standardized warm-up (Supplementary Material, Table S3), to ensure that potential changes between time points were due to fatigue-related factors, and not decreased muscle temperature.

The CMJ test without arm swing was used to assess jumping performance through the Optojump system (Microgate, Bolzano, Italy), as previously employed in basketball research [27]. Players started in the erect standing position (i.e., feet placed hip-width-to-shoulder-width apart and hands-on-hips) and were told to jump "as high and as fast as possible" using a self-selected countermovement depth. At each time point, players performed three CMJ trials (separated by 1 min of passive rest), with the best result used for analysis. This procedure has shown good reliability in previous research [28].

Additionally, as used in previous basketball research [22], 10- and 20-m maximal sprint times were recorded during a 20-m sprint test with a 10-m split, using three sets of timing gates (Witty, Microgate, Bolzano, Italy) positioned at 0, 10, and 20 m from the start, respectively. Players started 50 cm behind the first gate, to avoid involuntary triggering of timing in the start position. Two sprint trials (separated by 2 min of passive rest) were performed at each time point, with the best result used for analysis. This procedure has shown good reliability in previous research [29].

Of the 84 scheduled measurements for each test (i.e., jumping and sprinting), 2 were missing due to participants' unavailability (i.e., both at 24 h post-training).

Physiological assessment

Bluetooth HR monitors (H10, Polar Electro Oy, Kempele, Finland) were used to assess HRV in supine position. Players were asked to record HRV for 90 s using the Elite HRV smartphone application (Ashville, North Carolina, USA), a valid and reliable tool to assess HRV during ultra-short recordings [30]. The log-transformed squared root of the mean sum of the squared differences between R-R intervals (Ln-rMSSD) was calculated to investigate parasympathetic autonomic activity [27]. Of the 84 scheduled measurements, 6 were excluded due to poor signal quality ($n = 4$) or participants' unavailability ($n = 2$, as mentioned earlier).

Perceptual assessment

According to previous research [31], Borg's CR10 scale of perceived muscle pain for lower limbs between 0 ("nothing at all") and 11 ("maximum pain") was used to assess muscle soreness in a static condition (i.e., standing without moving). Additionally, muscle soreness was measured in the quadriceps muscles while performing a deep squat (i.e., dynamic condition), through a previously used visual analog scale from 0 ("none") to 10 points ("intolerably intense") [32]. Finally, the overall perception of fatigue was obtained using the previously validated Rating-of-Fatigue scale [33], ranging between 0 ("not fatigued at all") and 10 ("total fatigue and exhaustion—nothing left").

Due to the above-mentioned unavailability of 2 participants at 24 h post-training, perceptual data are reported for 12 players (rather than 14), as nonparametric methods to appropriately handle missing values in ordinal data were not available (as opposed to continuous data; see "Statistical analysis" section).

External and internal load monitoring

External load was measured using accelerometry (ClearSky T6, Catapult Innovations, Melbourne, Australia) as previously described [2,34]. Briefly, session PlayerLoad (PL, arbitrary units [AU]) was computed as the sum of the accelerations across all axes during movement (derived from the instantaneous rate of change of acceleration), while PL/min (AU/min) was calculated by dividing PL by session duration (min) [2]. Furthermore, the highest HR value recorded during any of the two training sessions (HR_{peak}) was identified, and exercise intensity was calculated as the average percentage of HR_{peak} throughout each session ($\%HR_{peak}$). Finally, RPE scores were collected (using the paper and pencil method, without peer influence [35]) approximately 10 min post-training through the modified CR10 scale [36], and then multiplied by session duration (min) to determine session-RPE load (s-RPE, AU).

Statistical analysis

Descriptive statistics (mean ± standard deviation [continuous data] or median ± interquartile range [ordinal data]) were calculated for each variable. Separate linear mixed models, which correctly deal with missing values and repeated measures, were used for each continuous dependent variable (CMJ height, 10- and 20-m sprint times, Ln-rMSSD) to calculate the effect of time, intervention, and time × intervention interaction. In these models, time and intervention represented the fixed effects, while player represented the random effect. In case of statistically significant differences, Bonferroni posthoc analyses were run. All variables showed normally distributed residuals (Shapiro–Wilk test $P > 0.05$), except for 20-m sprint times. However, violations of this assumption within linear mixed models are rarely problematic [37], and the use of alternative methods (e.g., nonparametric tests, generalized linear models) may affect the reliability of conclusions to a greater extent [38]. To assess the effect of time for ordinal data (muscle soreness and perceived fatigue), separate Friedman tests (i.e., one for each intervention) were used. In case of statistically significant differences, posthoc analyses were run using the Wilcoxon test with Bonferroni correction. The Wilcoxon test was also used to compare ordinal data between interventions at corresponding time points. After assessing the normal distribution assumption via the Shapiro–Wilk test ($P > 0.05$), differences in PL, PL/min, $\%HR_{peak}$, and s-RPE load data between CAF and CON were assessed using paired-samples t-tests. The magnitude of differences for pairwise comparisons was assessed using Cohen's d (with 95% confidence intervals [CI]) for parametric analyses and was interpreted as: *trivial* (<0.20), *small* (0.20–0.59), *moderate* (0.60–1.19), *large* (1.20–1.99), and *very large* (≥2.0) [39]. For non-parametric analyses, ES was calculated using the r value (Wilcoxon z value/$\sqrt{N}$) and interpreted as: *small* (0.10–0.29), *moderate* (0.30–0.49), and *large* (≥0.50) [40]. Statistical significance was set at $P < 0.05$ and all analyses were carried out using the Jamovi software package for Windows (version 2.3.28, Sydney, Australia).

Table 1
Differences in external and internal load between interventions

Load variables	CAF	CON	P value	MD (95% CI)	ES (95% CI)	ES interpretation
PL (AU)	456.6 ± 82.2	448.8 ± 78.0	0.774	7.72 (−49.98 to 65.41)	0.08 (−0.48 to 0.65)	*Trivial*
PL/min (AU/min)	5.7 ± 1.0	5.6 ± 1.0	0.825	0.08 (−0.67 to 0.83)	0.07 (−0.50 to 0.63)	*Trivial*
$\%HR_{peak}$	79.1 ± 6.8	80.0 ± 6.0	0.694	−0.86 (−5.52 to 3.81)	−0.12 (−0.68 to 0.45)	*Trivial*
s-RPE (AU)	320.0 ± 113.1	366.7 ± 175.5	0.131	−46.67 (−109.70 to 28.64)	−0.47 (−1.06 to 0.14)	*Small*

$\%HR_{peak}$, average session heart rate, measured as the percentage of peak heart rate; AU, arbitrary units; CAF, caffeine supplementation; CI, confidence interval; CON, placebo intervention; ES, effect size; MD, mean difference; PL, PlayerLoad; PL/min, PlayerLoad per min; s-RPE, session-Rating of Perceived Exertion.

Results

Table 1 shows external and internal load data in each training session. Non-significant ($P > 0.05$), *trivial-to-small* differences were found for PL, PL/min, $\%HR_{peak}$ and s-RPE between interventions.

The time course of the investigated performance, physiological, and perceptual measures throughout the study is illustrated in Figures 2 and 3. Additionally, Tables S4 to S10 (Supplementary Material) report individual data for each participant, including percentage change across time points for both interventions.

No significant effects of time × intervention interaction or intervention ($P > 0.05$) were observed for any of the investigated continuous variables. A significant effect of time was found for CMJ height ($P < 0.001$), 10-m sprint times ($P = 0.024$), and Ln-rMSSD ($P < 0.001$), but not 20-m sprint times ($P = 0.674$). Posthoc analysis showed lower values for CMJ height (range of individual changes from pre-to-post-training for CAF: −8.2% to 5.1% and CON: −20.4% to 4.9%; from post-training to 24 h post-training for CAF: −5.3% to 18.2% and CON: 0.6% to 22.0%) and Ln-rMSSD (range of individual changes from pre-to-post-training for CAF: −62.6% to −3.2% and CON: −60.0% to −7.9%; from post-training to 24 h post-training for CAF: −23.7% to 134.6% and CON: 12.6% to 121.8%) at post-training compared with all other time points ($P < 0.001$, ES = −1.41 to −1.98, *large*), while 10-m sprint times deteriorated from pre-to-post-training ($P = 0.029$, ES = 0.69 [95% CI: −1.09 to −0.27], *moderate* [range of individual changes for CAF: −2.8% to 7.7% and CON: −4.3% to 7.9%]).

Regarding perceptual data, no significant, direct differences were found between interventions at corresponding time points ($P > 0.05$). Conversely, a significant effect of time was found for static (CAF: $P = 0.004$; CON: $P < 0.001$) and dynamic (both CAF and CON: $P < 0.001$) muscle soreness in both interventions. Posthoc analysis revealed significantly higher values at post-training, compared with pre-training, for static ($P = 0.004$, $r = 0.60$, *large*) and dynamic ($P \leq 0.006$, $r = 0.58–0.61$, *large*) muscle soreness in both CAF (range of individual changes: 0%–567%) and CON (range of individual changes: 0%–700%). Furthermore, static muscle soreness in CON ($P = 0.010$, $r = 0.53$, *large* [range of individual changes: −25% to 700%]) and dynamic muscle soreness in CAF ($P = 0.005$, $r = 0.58$, *large* [range of individual changes: 0%–200%]) were significantly higher than pre-training levels at 24 h post-training. Similar to muscle soreness, a significant effect of time was observed for perceived fatigue in both CAF ($P = 0.002$) and CON ($P < 0.001$). Posthoc tests showed increased fatigue from pre-to-post-training in both interventions ($P \leq 0.006$, $r = 0.57–0.60$, *large* [range of individual changes for CAF: −17% to 400% and CON: 0%–200%]), and at post-training compared to 24 h post-training, only in CON ($P = 0.003$, $r = 0.61$, *large* [range of individual changes: 0%–63%]).

Discussion

To the best of the authors' knowledge, this study is the first to analyze the impact of caffeine supplementation on post-exercise fatigue responses among basketball players. The present findings indicate that pre-training supplementation did not impact the investigated outcome measures at any time point, as indicated by the lack of statistically significant differences between interventions.

Previous research [7] has provided a considerable amount of evidence in support of the acute ergogenic effects of caffeine on athletic performance. Specifically, review studies among basketball players [8,9] demonstrated that the same caffeine dosage utilized in the present study (3 mg/kg body weight) generally had a beneficial, acute impact on jumping and sprinting abilities when performance was analyzed in a rested condition following caffeine supplementation. Building on such research, the present study assessed performance following basketball training (rather than in a rested state), to explore its potential role in mitigating fatigue. Our findings indicate a lack of significant, acute differences between CAF and CON in terms of CMJ and sprint performance. A potential explanation for this discrepancy may be related to the timing of ingestion, as previous basketball research typically administered caffeine ∼60 min before testing [8,9], when blood caffeine concentrations are believed to peak [7]. This timing could maximize caffeine antagonism of adenosine receptors in the central nervous system, boosting neurotransmitter release and motor unit recruitment to enhance performance [7]. However, considering that caffeine levels generally remain elevated for hours following ingestion (half-life: ∼4 to 6 h [7]), it is plausible that its positive effects on performance (if present) would still manifest at the end of training (i.e., ∼80 min post-ingestion) in the present study. Interestingly, however, a previous review [7] suggested that—when the goal is to improve performance under fatigue—caffeine intake during exercise (particularly, close to the final stages) may be more beneficial than pre-exercise supplementation. Hence, future investigations are warranted to examine such supplementation protocols among basketball players. Regarding the effects of caffeine on next-day performance (i.e., 24 h post-training), we hypothesized that caffeine could increase the total amount of work performed during training (i.e., PL, PL/min, $\%HR_{peak}$), potentially decreasing performance [12]. However, this dose-response effect (i.e., between training loads and fatigue responses) did not seem to occur, as PL, PL/min and $\%HR_{peak}$ were statistically comparable across interventions, resulting in similar recovery time courses between CAF and CON. It is worth noting that we did not perform inferential analysis on the influence of habitual caffeine consumption on performance metrics, a factor that previous research has

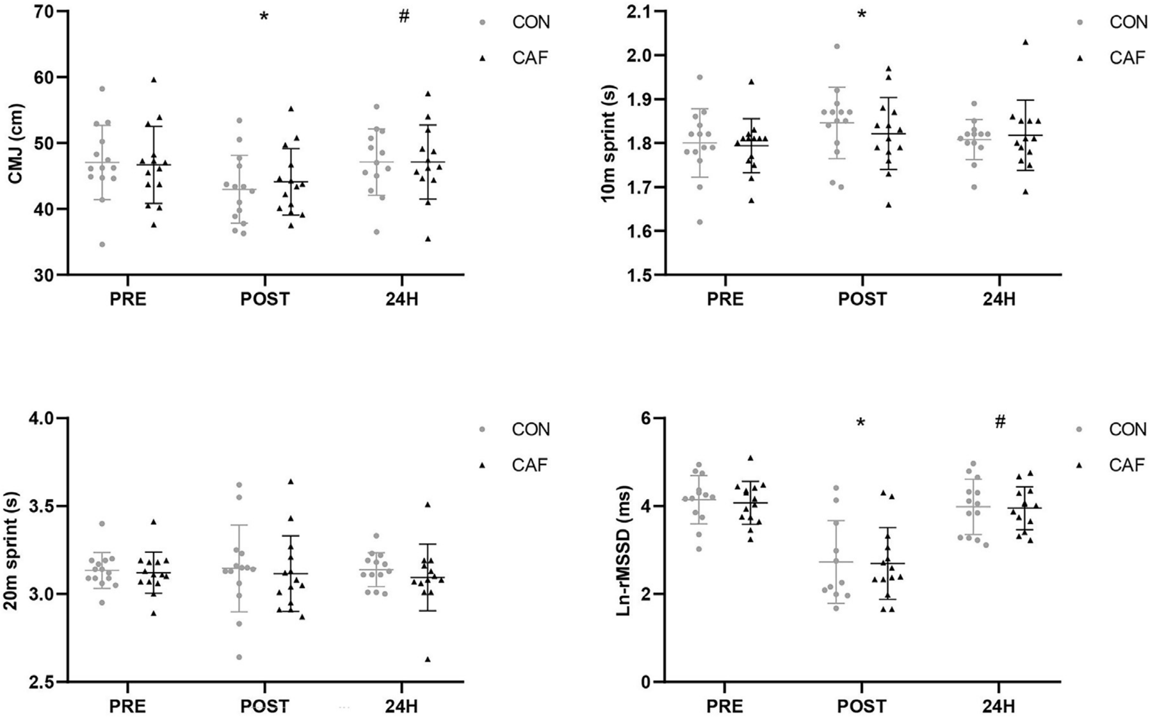

Fig. 2. Time course of jump height, 10-m sprint times, 20-m sprint times, and heart rate variability throughout the study period. Data are presented as mean ± standard deviation, with individual values represented by dots (CON) and triangles (CAF). The pooled effects of time are marked as follows: * significant difference with pre-training; # significant difference with post-training. Statistical significance is set at $P < 0.05$. 24H, 24 hours post-training; CAF, caffeine supplementation; CMJ, countermovement jump; CON, placebo intervention; Ln-rMSSD, log-transformed squared root of the mean sum of the squared differences between R-R intervals; POST, post-training; PRE, pre-training.

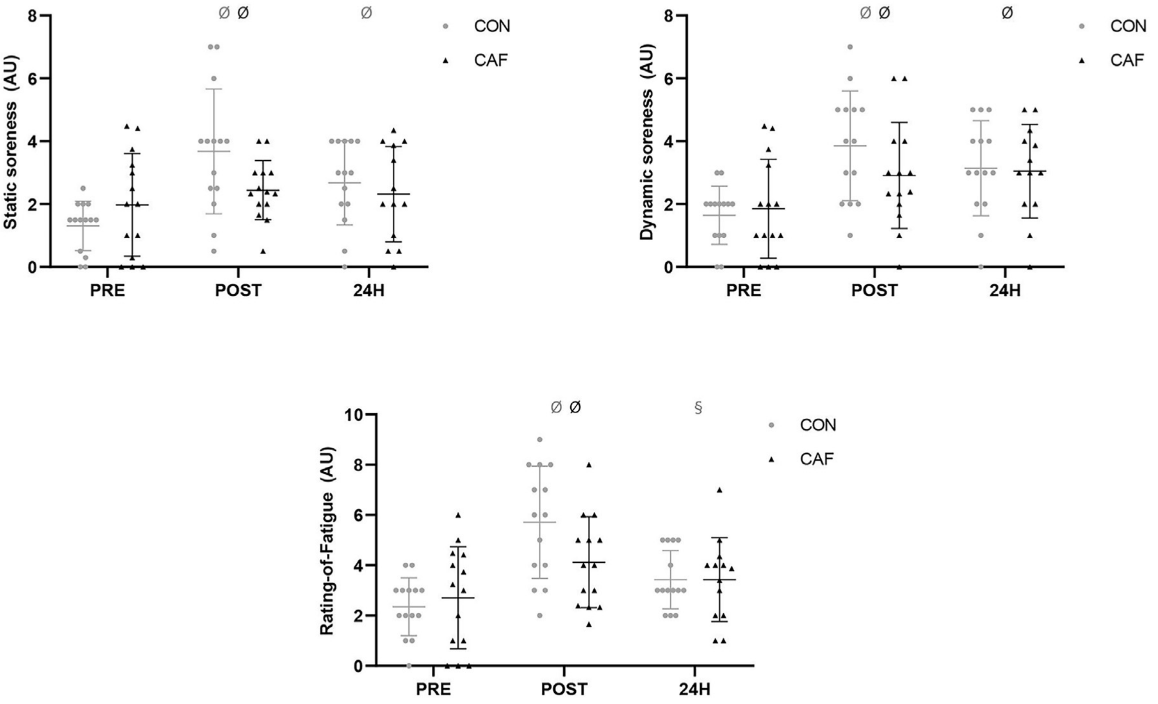

Fig. 3. Time course of static muscle soreness, dynamic muscle soreness, and perceived fatigue throughout the study period. Data are presented as median ± interquartile range, with individual values represented by dots (CON) and triangles (CAF). Statistically significant differences within each intervention are reported in grey for CON and black for CAF, and marked as follows: Ø significant difference with pre-training; § significant difference with post-training. Statistical significance is set at $P < 0.05$. 24H, 24 hours post-training; AU, arbitrary units; CAF, caffeine supplementation; CON, placebo intervention; POST, post-training; PRE, pre-training.

suggested might reduce the ergogenic effects of caffeine (i.e., with habitual caffeine consumers potentially experiencing fewer performance benefits compared to non-users) [41]. However, a recent meta-analysis [42] revealed that this phenomenon does not seem to occur across a variety of exercise modalities (e.g., endurance, strength/power tasks), sexes, and fitness levels. Given these findings, further research is needed before postulating that habitual caffeine consumption can influence its ergogenic effect among basketball players.

In addition to disrupting physical performance, basketball training and competition have been shown to suppress parasympathetic cardiac activity [1], an important component of post-exercise recovery. Crucially, previous research [18,19] suggested that caffeine may exacerbate this phenomenon and delay post-exercise parasympathetic reactivation, due to its capacity to stimulate catecholamine release and modify cardiac autonomic modulation [20]. However, the present findings did not highlight any significant difference in Ln-rMSSD between interventions, suggesting a negligible impact of caffeine on HRV. Such findings align with a recent meta-analysis [20], showing that—overall—pre-exercise caffeine ingestion (~3 to 6 mg/kg body weight) may not affect post-exercise parasympathetic reactivation. Nevertheless, it should be noted that findings extrapolated from individual studies were somewhat mixed, with the authors attributing this heterogeneity to variations in research methodologies across studies [20]. Specifically, factors such as timing of administration, participants' fitness level, time of day, and genetic variability have been suggested to influence the effect of caffeine on post-exercise parasympathetic reactivation [43], which likely explains inconsistencies across the scientific literature [20]. In summary, basketball-specific data from the present study indicate that the supplementation protocol used here did not significantly affect parasympathetic reactivation in basketball players.

In addition to its purported effects on performance and cardiac autonomic activity, previous research [7,11] suggested that caffeine may exert a beneficial effect on subjective perceptions of muscle soreness and fatigue, likely due to its adenosine-antagonizing effects, leading to blunted pain perception and inflammation in neural tissues [10]. However, muscle soreness and perceived fatigue displayed a similar behavior between CAF and CON in the present study, indicating the absence of a significant caffeine effect. These findings are somewhat in contrast with previous systematic reviews, indicating that caffeine supplementation generally reduced muscle soreness [10] and perceived fatigue [44] across various samples (i.e., recreational cyclists, collegiate athletes, untrained college students, resistance-trained participants, soccer players), compared to placebo. However, findings from the aforementioned reviews are somewhat mixed, with two of six studies in Caldas et al. [10] and one of three in Mielgo-Ayuso et al. [44] reporting a detrimental or negligible effect of caffeine on perceptual components of fatigue, suggesting that its impact is not yet fully confirmed [12]. Furthermore, it is important to note that substantial methodological differences exist between the present study and previous research. Specifically, it appears that post-exercise or combined (i.e., both pre- and post-exercise) caffeine usage (rather than exclusively pre-exercise) was most beneficial to reduce muscle soreness up to 72 h post-exercise (a timeframe not investigated here) [10]. Accordingly, given that most caffeine is typically removed from circulation within ~7 h post-ingestion [11], consuming maintenance doses during the recovery period (e.g., 24 or 48 h after exercise) may increase its capacity to mitigate fatigue symptoms [11]. This assumption is based on the ability of caffeine to antagonize adenosine receptors, which prevents pain signals (as adenosine molecules cannot bind) [7,11,45]. Specifically, given that previous research suggests that these effects may only be transient [45], this supports the rationale for consuming maintenance doses to sustain caffeine-related benefits. Therefore, future basketball-specific research could provide valuable insights into the use of repeated caffeine supplementation over a longer time window (e.g., up to 72 h post-exercise), aiming to benefit perceptual components of fatigue.

General remarks and limitations

When consulting existing research into the effectiveness of caffeine for fatigue and recovery management, it appears clear that methodological aspects such as the type of investigated sample, fatigue-inducing exercise protocol used, outcome measures used to detect fatigue, caffeine dosages, timing, and supplementation strategies can introduce considerable variability across studies [10,12]. Accordingly, we strived to maximize ecological validity, by utilizing a specific protocol (i.e., basketball training session) to induce fatigue in our sample, and by employing performance tests (i.e., jumping and sprinting) that are highly relevant to basketball [1]. Additionally, a caffeine dosage of 3 mg/kg body weight was selected due to its proven effectiveness across a multitude of basketball-directed studies [8,9]. Simultaneously, this dosage appears optimal when the intent is to combine the benefits of caffeine with a low prevalence of side effects [46], which is an important consideration in applied sport settings.

Despite the above-mentioned considerations, some limitations should be acknowledged. First, the participants included in this study competed in male amateur basketball leagues, meaning that the present findings might not apply to players of different sex, age, or competitive level. Consequently, further research is warranted to establish whether the supplementation protocol used in this study would be effective in samples with different characteristics, as the factors mentioned above may influence both fatigue responses and the effects of caffeine supplementation among basketball athletes [1,7]. Second, only physical performance was examined here, while other aspects that may contribute to basketball success (e.g., technical or cognitive performance) were not analyzed. Thus, future studies involving the measurement of such outcomes could provide additional insights. Lastly, genetic factors that may influence individual responses to caffeine ingestion [7] were not assessed in the present study. Future research including this component may enhance the understanding of the role of caffeine for fatigue and recovery management in basketball.

Conclusions

The present findings suggest that—although it did not appear to interfere with post-exercise recovery dynamics—pre-exercise caffeine ingestion (3 mg/kg body weight) had no significant benefit on performance, cardiac parasympathetic reactivation, muscle soreness, and perceived fatigue in amateur basketball players following a training session (both acutely and at 24 h post-training). Therefore, the present data suggest that pre-exercise caffeine supplementation using a single dose of 3 mg/kg body weight did not seem to provide significant benefits in terms of performance, physiological and perceptual fatigue in the investigated sample. Nevertheless, future research is warranted to examine different supplementation patterns. Specifically, providing additional caffeine doses closer to the end of exercise, along with maintenance doses during the recovery period (e.g., 24–48 h post-exercise), may enhance the impact of caffeine on fatigue mitigation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

CRediT authorship contribution statement

Marco Pernigoni: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Leonardo Cesanelli:** Writing – review & editing, Visualization, Software, Methodology, Conceptualization. **Lukas Šimkus:** Writing – review & editing, Resources, Project administration, Investigation. **Harshvardhan Shah:** Writing – review & editing, Methodology, Investigation. **Julija Gorbas:** Writing – review & editing, Resources, Investigation. **Francesco Coletta:** Writing – review & editing, Resources, Investigation. **Cem Rifat Toper:** Writing – review & editing, Resources, Investigation. **Daniele Conte:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization.

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Supplementary materials

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