JPMHR Journal of Precision Medicine and Health Research

Volume 3, Issue 2, 2026
e-ISSN: 3106-9495
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Article ID: 61

Original Article

Comparative Effects of Pre-Exercise and Mid-Exercise Caffeine Ingestion Combined with Pranayama on Cardiorespiratory Endurance and Physical Fitness in Runners

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Received: 25 September 2026 | Revised: 30 September 2026 | Accepted: 04 October 2026 | Published: 15 October 2026

ARTICLE INFORMATION

Article Type: Original Article

How to Cite: Iqbal M, Memon AG, Babur MN, Javed F, Maryam L, Iqbal A. Comparative Effects of Pre-Exercise and Mid-Exercise Caffeine Ingestion Combined with Pranayama on Cardiorespiratory Endurance and Physical Fitness in Runners. Journal of Precision Medicine and Health Research. 2026;3(2).

Article ID: 61

DOI: https://doi.org/10.68279/en3r1153

Article Link: https://jpmhr.com/index.php/jpmhr/article/view/61

Declarations: See end of article.

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ABSTRACT

Background: Caffeine supplementation and pranayama are used to support exercise performance; however, the influence of caffeine-ingestion timing during combined interventions remains uncertain. **Objective:** To compare pre-exercise and mid-exercise caffeine ingestion combined with pranayama on cardiorespiratory endurance and physical fitness among runners. **Methods:** A two-arm randomized clinical trial involved 36 healthy male runners aged 18–35 years recruited from three fitness centers. Participants were allocated equally to pre-exercise caffeine (Group A) or mid-exercise caffeine (Group B), with both groups receiving supervised pranayama and standardized running exercise. Outcomes included the Plank Test, Hexagon Agility Test, 20-Meter Sprint Test, and Cooper 12-Minute Run Test. Paired-samples t-tests assessed within-group changes, while unadjusted independent-samples comparisons evaluated between-group differences. **Results:** Both groups demonstrated improvements across all outcomes (reported $p < 0.05$). Post-intervention comparisons favored Group A for plank endurance (mean difference: 8.17 s; 95% CI: 1.07–15.27; $p = 0.0255$), agility (−0.80 s; 95% CI: −1.27 to −0.33; $p = 0.0015$), sprint performance (−0.10 s; $p = 0.0174$), and Cooper running distance (75.00 m; $p = 0.0418$). After exploratory multiplicity adjustment, only the agility comparison remained statistically significant. **Conclusion:** Pre-exercise caffeine combined with pranayama was associated with more favorable post-intervention performance, particularly agility, although unadjusted analyses and the small sample limit definitive conclusions about superiority. **Keywords:** Caffeine; Pranayama; Runners; Cardiorespiratory Endurance; Physical Fitness; Exercise Performance.

Introduction

Cardiorespiratory endurance and physical fitness are essential determinants of running performance, particularly in individuals engaged in regular endurance training. Successful running performance depends on the coordinated functioning of the cardiovascular, respiratory, and musculoskeletal systems to maintain oxygen delivery, energy production, and muscular activity during sustained exercise. Maximal oxygen uptake (VO_2max), aerobic capacity, and running efficiency are important physiological determinants of endurance performance, while muscular endurance, agility, and running speed contribute to overall athletic fitness (1,2). Evidence from exercise-training research indicates that structured physical conditioning can improve several performance-related characteristics in middle- and long-distance runners (3). Consequently, identifying effective strategies to optimize physical fitness and endurance remains an important consideration in sports science, physiotherapy, and athletic training.

Caffeine is among the widely investigated nutritional ergogenic aids used to enhance exercise performance. Its principal mechanism involves antagonism of adenosine receptors within the central nervous system, potentially increasing alertness, reducing perceived exertion, and improving exercise tolerance. Previous research has demonstrated that caffeine supplementation may enhance endurance performance, particularly during prolonged or demanding physical activity (4,5). However, the magnitude of these effects may depend on several factors, including caffeine dose, individual sensitivity, habitual caffeine consumption, and the characteristics of the exercise being performed. The literature also emphasizes the importance of investigating the conditions under which caffeine improves athletic performance rather than assuming a uniform response across exercise modalities and populations (6). Although caffeine supplementation may provide performance-related benefits, adverse effects and individual tolerability require consideration when incorporating it into exercise programs (7).

The timing of caffeine ingestion represents another potentially important factor influencing its ergogenic effects. Caffeine is commonly consumed before exercise to allow absorption and the development of its physiological effects during physical activity. Nevertheless, caffeine administration during exercise may offer a different pattern of exposure, particularly when exercise continues for a prolonged period. The potential effectiveness of these approaches may depend on the interval between ingestion and performance assessment, the duration and intensity of exercise, and individual responses to caffeine. Existing literature has examined caffeine supplementation under different sporting conditions, but uncertainty remains regarding how administration timing influences performance across different physical fitness outcomes (4,6). Furthermore, research examining caffeine-related performance enhancement has highlighted the importance of contextual factors and psychological responses when interpreting the effects of supplementation (8). These considerations support further direct comparisons of caffeine administration strategies under standardized exercise conditions.

Alongside nutritional supplementation, breathing-based interventions have received attention as complementary approaches to improving respiratory regulation and exercise-related functioning. Pranayama, a traditional yogic breathing practice, involves controlled regulation of breathing patterns through techniques that may incorporate slow breathing, altered respiratory rhythm, and breath retention. Physiological explanations have suggested that slow, controlled breathing may influence autonomic nervous system activity and respiratory regulation (9). Research investigating structured pranayama interventions has also reported changes in pulmonary function indices following repeated practice, suggesting its potential relevance to respiratory conditioning (10). However, improvements in

pulmonary function or autonomic regulation should not automatically be interpreted as equivalent to improvements in athletic performance. Further investigation is therefore needed to establish how breathing interventions relate to functional outcomes such as muscular endurance, agility, sprint performance, and distance-running capacity.

The combination of caffeine supplementation and pranayama may represent a complementary approach to exercise-performance optimization because the two interventions target different aspects of physiological functioning. Caffeine primarily influences central nervous system activity and perceived exercise demands, whereas pranayama may influence breathing regulation and autonomic responses. Nevertheless, evidence supporting these interventions individually does not necessarily establish an additional or synergistic benefit when they are used together. Existing research has investigated caffeine supplementation in relation to athletic performance and sleep-related considerations, emphasizing the need to balance potential ergogenic benefits against individual responses and recovery requirements (11). Experimental research has also examined the interaction between caffeine-related physiological and psychological influences on exercise performance (8). Despite these developments, the relative effects of administering caffeine before exercise or during exercise while maintaining an identical pranayama and running program remain insufficiently established within the literature represented in this manuscript.

This evidence gap is particularly relevant to recreationally trained runners, for whom practical interventions should be feasible, reproducible, and applicable within regular exercise routines. Although caffeine supplementation and breathing practices have been investigated separately, direct comparisons of caffeine-ingestion timing in conjunction with structured pranayama remain limited. Furthermore, physical fitness is multidimensional, and an intervention associated with improved endurance may not produce equivalent effects on muscular endurance, agility, or sprint performance. Assessing several functional outcomes may therefore provide a broader understanding of differences between caffeine-timing strategies. The Plank Test, Hexagon Agility Test, 20-Meter Sprint Test, and Cooper 12-Minute Run Test provide distinct field-based assessments of these performance domains. Comparing the two caffeine-timing strategies while both groups receive the same pranayama and running program may help clarify whether the timing of caffeine administration is associated with differences in these outcomes. However, such a comparison cannot independently establish the effects of caffeine or pranayama because both interventions are administered in each group.

Therefore, the present randomized clinical trial aimed to compare the effects of pre-exercise and mid-exercise caffeine ingestion, each combined with supervised pranayama and a standardized running protocol, on muscular endurance, agility, sprint performance, and cardiorespiratory endurance among healthy male runners aged 18–35 years. Physical performance was assessed using the Plank Test, Hexagon Agility Test, 20-Meter Sprint Test, and Cooper 12-Minute Run Test. The primary research question was whether pre-exercise and mid-exercise caffeine administration, when combined with the same pranayama and running intervention, resulted in different changes in the measured physical fitness and endurance outcomes.

Materials and Methods

A two-arm, parallel-group randomized clinical trial was conducted to compare the effects of pre-exercise and mid-exercise caffeine ingestion combined with pranayama on cardiorespiratory endurance and physical fitness among healthy male runners. The study was carried out at Level Fitness Gym, 5 Fitness Gold Gym, and Cross Fitness Gym over a reported period of three to six months following ethical approval. The experimental comparison involved two groups receiving the same supervised pranayama intervention and standardized running protocol, with caffeine administration timing serving as the principal between-group intervention variable. The study was designed to evaluate differences in muscular endurance, agility, sprint performance, and cardiorespiratory endurance following the intervention.

The target population consisted of healthy male runners aged 18–35 years who had participated in regular running activities for approximately 6–12 months. Participants were recruited from the selected fitness facilities using a non-probability convenience sampling technique. Eligible individuals were healthy recreational runners who met the specified age and running-experience criteria and were willing to participate in the intervention. Individuals with diagnosed cardiovascular, respiratory, or metabolic disorders were excluded. Additional exclusion criteria included known caffeine sensitivity, habitual caffeine consumption exceeding 400 mg/day, medication use potentially affecting cardiovascular or exercise responses, smoking or substance abuse history, recent musculoskeletal injury, and concurrent participation in another clinical trial. Written informed consent was obtained from all participants before enrollment.

The sample size was calculated using G*Power version 3.1, with an assumed effect size of 0.30, significance level of 0.05, and statistical power of 80%. The calculation indicated a minimum required sample of 34 participants. To account for potential participant withdrawals, the target sample was increased to 36. Following recruitment, 36 eligible male runners were randomly allocated in a 1:1 ratio into two intervention groups, with 18 participants in each group. Group A received caffeine before exercise, whereas Group B received caffeine during exercise. The same eligibility criteria, intervention components, and outcome-assessment procedures were applied to both groups.

Participants assigned to Group A received caffeine at a dose ranging from 3 to 6 mg/kg of body weight approximately 30–45 minutes before exercise. Caffeine administration was followed by 10–15 minutes of supervised pranayama and participation in the standardized running protocol. Participants allocated to Group B received caffeine within the same reported dose range of 3–6 mg/kg of body weight at the midpoint of the exercise session. Both groups followed the same supervised pranayama and running intervention, with caffeine-ingestion timing representing the intended experimental difference. The use of a body-weight-based caffeine dose was consistent with the broader approach to caffeine supplementation described in the sports-performance literature, although individual responses to supplementation may vary (4,5).

Pranayama was incorporated into the intervention as a supervised breathing practice intended to complement the running program. The breathing intervention was administered to both groups throughout the intervention period, with the explicitly reported session duration being 10–15 minutes. The inclusion of pranayama was supported by physiological literature describing the potential influence of controlled breathing on respiratory regulation and autonomic nervous system activity (9). Research involving structured pranayama interventions has also examined changes in pulmonary function following repeated practice (10). In the present trial, pranayama was maintained as a common intervention component in both groups to permit comparison of the two caffeine-ingestion strategies under otherwise similar reported exercise conditions.

Data collection involved assessment of participant characteristics and physical performance before and after the intervention. Baseline demographic and anthropometric variables included age, height, body weight, and body mass index (BMI). Age was expressed in years, height in centimeters, body weight in kilograms, and BMI in kilograms per square meter. These characteristics were used to describe the

study population and examine the baseline distribution of participant characteristics across the two intervention groups. Physical performance was evaluated using four field-based tests covering different components of fitness and endurance.

Core muscular endurance was assessed using the Plank Test, which measures the duration for which an individual can maintain a standardized plank position. Performance was recorded in seconds, with a longer holding duration indicating greater isometric core muscular endurance. Agility was assessed using the Hexagon Agility Test, which evaluates the ability to perform rapid multidirectional movements around a hexagonal pattern. Completion time was recorded in seconds, with shorter times representing better agility performance. Running speed was evaluated using the 20-Meter Sprint Test, in which participants performed a sprint over a distance of 20 meters. Sprint performance was recorded in seconds, with a shorter completion time indicating faster running speed. These field-based measures were selected to evaluate distinct components of physical fitness relevant to running performance.

Cardiorespiratory endurance was evaluated using the Cooper 12-Minute Run Test, a field-based exercise test that assesses the distance covered during 12 minutes of continuous running. Participants were assessed according to the total distance completed within the specified test duration, recorded in meters. Greater distance was interpreted as better aerobic endurance performance. The Cooper test was used as a functional indicator of cardiorespiratory endurance rather than a direct measurement of maximal oxygen consumption. The selection of running-related performance measures was consistent with the broader physiological and performance characteristics commonly evaluated in endurance athletes (1,2).

All four physical performance outcomes were assessed before and after the intervention in both groups. The pre-intervention assessment established baseline performance, while the post-intervention assessment was used to determine changes following exposure to the assigned caffeine-timing strategy combined with supervised pranayama and running exercise. The Plank Test, Hexagon Agility Test, 20-Meter Sprint Test, and Cooper 12-Minute Run Test were treated as continuous outcome variables. Improvements were defined as increased plank holding time and Cooper running distance or decreased hexagon agility and 20-meter sprint completion times. Within-group changes were evaluated by comparing pre-intervention and post-intervention measurements, while between-group comparisons examined differences in performance between the pre-exercise and mid-exercise caffeine groups.

Measures were incorporated to reduce potential measurement and analytical bias. Both intervention groups received the same reported pranayama and running protocols, with the timing of caffeine administration constituting the principal intended difference between groups. Outcome assessment was performed by an assessor blinded to intervention allocation. Additionally, the statistician analyzed data using coded group identities to reduce the potential influence of group identification during analysis. The use of common outcome measures in both groups supported consistent comparison of physical performance. Baseline participant characteristics were summarized separately for each group to describe their demographic and anthropometric distributions.

Data were entered and analyzed using IBM SPSS Statistics version 27.0. Descriptive statistics were calculated for demographic characteristics, anthropometric variables, and physical performance outcomes. Continuous variables were summarized as mean ± standard deviation for approximately normally distributed data, with median and interquartile range considered where appropriate. Categorical variables were expressed as frequencies and percentages. The Shapiro–Wilk test was used to assess the normality of continuous data. Paired-samples t-tests were applied to compare pre-intervention and post-intervention outcome measurements within each intervention group. Independent-samples t-tests were used to compare physical performance measures between Group A and Group B. Statistical significance was established at a two-sided p-value of less than 0.05, and a 95% confidence level was specified for statistical inference. The reported analyses comprised within-group comparisons and unadjusted between-group comparisons.

Ethical approval was obtained from the Research Review Board of the Department of Physical Therapy and Rehabilitation Sciences, Faculty of Allied Health Sciences, The Superior University, Lahore. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Written informed consent was obtained from all participants before their inclusion in the trial.

Results

A total of 36 healthy male runners were included in the study, with 18 participants allocated to the pre-exercise caffeine group (Group A) and 18 to the mid-exercise caffeine group (Group B). The mean age was 24.56 ± 4.96 years in Group A and 29.61 ± 4.78 years in Group B, corresponding to a between-group difference of −5.05 years (95% CI: −8.35 to −1.75). Mean height, body weight, and BMI were comparable descriptively between groups. The baseline demographic and anthropometric characteristics are presented in Table 1.

Both intervention groups demonstrated changes in physical performance between the pre-intervention and post-intervention assessments (Table 2). Plank holding duration increased by 15.89 seconds in Group A and 8.00 seconds in Group B. Hexagon agility completion time decreased by 1.41 seconds and 0.60 seconds, respectively, while 20-meter sprint time decreased by 0.19 seconds in Group A and 0.10 seconds in Group B. Cooper 12-minute run distance increased by 148.89 meters in Group A and 72.78 meters in Group B. The original paired-samples analyses reported $p < 0.05$ for all within-group comparisons.

Table 1. Baseline demographic and anthropometric characteristics of participants (N = 36)

Characteristic	Group A (n = 18)	Group B (n = 18)	Mean difference (95% CI)
Age (years)	24.56 ± 4.96	29.61 ± 4.78	−5.05 (−8.35 to −1.75)
Height (cm)	174.83 ± 4.63	175.50 ± 4.06	−0.67 (−3.62 to 2.28)
Weight (kg)	71.61 ± 4.30	71.44 ± 3.18	0.17 (−2.40 to 2.74)
BMI (kg/m²)	23.04 ± 0.83	23.23 ± 0.58	−0.19 (−0.68 to 0.30)

Values are mean ± SD unless otherwise indicated. Group A: pre-exercise caffeine; Group B: mid-exercise caffeine. Mean difference = Group A − Group B. CIs were derived using Welch's independent-samples method. BMI = body mass index; CI = confidence interval; SD = standard deviation. Baseline hypothesis-testing p-values are omitted because allocation was randomized.

Table 2. Pre-intervention, post-intervention and within-group changes in physical performance outcomes (N = 36)

Outcome	Group	Pre-intervention mean ± SD	Post-intervention mean ± SD	Mean change	Reported paired p
Plank test (s)	A	80.00 ± 10.00	95.89 ± 11.44	+15.89	<0.05
	B	79.72 ± 8.77	87.72 ± 9.40	+8.00	<0.05
Hexagon agility test (s)	A	18.24 ± 0.75	16.83 ± 0.72	−1.41	<0.05

Outcome	Group	Pre-intervention mean ± SD	Post-intervention mean ± SD	Mean change	Reported paired p
	B	18.23 ± 0.67	17.63 ± 0.67	−0.60	<0.05
20-meter sprint test (s)	A	3.67 ± 0.14	3.48 ± 0.12	−0.19	<0.05
	B	3.68 ± 0.13	3.58 ± 0.12	−0.10	<0.05
Cooper 12-minute run test (m)	A	2330.00 ± 103.13	2478.89 ± 108.40	+148.89	<0.05
	B	2331.11 ± 99.46	2403.89 ± 104.27	+72.78	<0.05

Group A: pre-exercise caffeine (n = 18); Group B: mid-exercise caffeine (n = 18). Mean change = post-intervention mean − pre-intervention mean. Positive changes represent increased plank duration or running distance; negative changes represent reduced test-completion times. Paired p-values are reproduced as reported in the manuscript and have not been independently recalculated. SD = standard deviation; s = seconds; m = meters.

Table 3. Unadjusted between-group comparisons of post-intervention physical performance outcomes (N = 36)

Outcome	Mean difference (95% CI)	Welch p	Hedges' g
Plank test (s)	8.17 (1.07 to 15.27)	0.0255	0.76
Hexagon agility test (s)	−0.80 (−1.27 to −0.33)	0.0015	−1.13
20-meter sprint test (s)	−0.10 (−0.18 to −0.02)	0.0174	−0.82
Cooper 12-minute run test (m)	75.00 (2.95 to 147.05)	0.0418	0.69

Group A: pre-exercise caffeine (n = 18); Group B: mid-exercise caffeine (n = 18). Mean difference = Group A − Group B. Confidence intervals and two-sided p-values were recalculated using Welch's independent-samples t-test from reported means, SDs and sample sizes. Hedges' g was calculated using the pooled SD with a small-sample bias correction. Positive effects favor Group A for plank duration and Cooper distance, while negative effects favor Group A for timed tests. Estimates are unadjusted for baseline outcome values and participant characteristics.

Unadjusted post-intervention comparisons demonstrated differences between the caffeine-timing groups across the four performance outcomes (Table 3). Plank endurance was greater in Group A, with a mean difference of 8.17 seconds (95% CI: 1.07 to 15.27; p = 0.0255; Hedges' g = 0.76). Hexagon agility completion time was shorter in Group A by 0.80 seconds (95% CI: −1.27 to −0.33; p = 0.0015; Hedges' g = −1.13). Similarly, 20-meter sprint time was shorter in Group A, with a mean difference of −0.10 seconds (95% CI: −0.18 to −0.02; p = 0.0174; Hedges' g = −0.82).

Cardiorespiratory endurance, assessed through the Cooper 12-Minute Run Test, also differed between the intervention groups at the post-intervention assessment. Participants in Group A covered a mean distance of 2478.89 ± 108.40 meters, compared with 2403.89 ± 104.27 meters in Group B. The unadjusted between-group mean difference was 75.00 meters (95% CI: 2.95 to 147.05; p = 0.0418), corresponding to a Hedges' g of 0.69.

Overall, the post-intervention comparisons favored the pre-exercise caffeine group across muscular endurance, agility, sprint performance, and running distance. Standardized post-intervention differences ranged in absolute magnitude from 0.69 to 1.13. These estimates describe unadjusted between-group differences at follow-up rather than baseline-adjusted differences in intervention-related change.

Discussion

The present study compared pre-exercise and mid-exercise caffeine ingestion combined with supervised pranayama and a standardized running protocol among healthy male runners. Both intervention groups demonstrated improvements in muscular endurance, agility, sprint performance, and cardiorespiratory endurance following the intervention. However, the pre-exercise caffeine group demonstrated more favorable post-intervention performance across all four outcomes. The largest standardized between-group difference was observed in agility, followed by sprint performance, muscular endurance, and cardiorespiratory endurance. Although these findings suggest that caffeine-ingestion timing may influence exercise-performance outcomes when combined with pranayama, the results should be interpreted in the context of the unadjusted comparisons, baseline participant characteristics, and the relatively small sample size.

The observed findings are broadly consistent with previous research supporting the ergogenic potential of caffeine supplementation during exercise. Doherty and Smith (2004), in a meta-analysis investigating caffeine ingestion and exercise testing, reported evidence supporting beneficial effects of caffeine on exercise performance (5). Similarly, Spriet (2014) reviewed the influence of caffeine supplementation on exercise and sports performance, emphasizing that caffeine may enhance endurance-related outcomes even at relatively low doses (4). These findings provide a physiological and performance-related context for the improvements observed in both intervention groups. However, the present study differs from previous caffeine investigations because both groups received caffeine alongside supervised pranayama and running exercise, with ingestion timing representing the principal experimental comparison. Consequently, the within-group improvements cannot be attributed exclusively to caffeine supplementation, as exercise training, breathing practice, and repeated exposure to performance testing may also have contributed.

The more favorable post-intervention performance observed in the pre-exercise caffeine group may be related to differences in caffeine availability during exercise. Caffeine acts primarily through antagonism of adenosine receptors, potentially influencing central nervous system activation, alertness, perceived exertion, and the ability to sustain physical effort. Its performance-related effects may vary according to ingestion timing, dosage, exercise intensity, and individual physiological responses (4,5). In the present study, caffeine administered approximately 30–45 minutes before exercise may have allowed greater exposure during the initial exercise period than caffeine administered at the midpoint of the running session. This difference could partly explain the observed performance pattern, particularly for activities requiring sustained muscular effort or rapid movement execution. Nevertheless, caffeine concentrations, absorption rates, perceived exertion, and neuromuscular activation were not directly measured. Therefore, these physiological explanations remain plausible mechanisms rather than experimentally confirmed pathways.

The findings concerning agility and sprint performance also warrant consideration in relation to previous research examining caffeine supplementation during intermittent and high-intensity activities. Diaz-Lara et al. (2024), in a systematic review and meta-analysis, investigated the effects of acute caffeine intake on performance in intermittent sports, providing evidence relevant to caffeine-related changes in sport-specific physical performance (12). The present study similarly demonstrated more favorable agility and sprint outcomes

in the pre-exercise caffeine group, although the population and intervention conditions differed. Unlike investigations focusing primarily on acute caffeine supplementation, the current trial incorporated pranayama and a running program in both intervention groups. Furthermore, the observed post-intervention sprint difference was relatively small in absolute terms, despite its standardized effect estimate. This distinction is important because statistical differences do not necessarily correspond to meaningful competitive advantages, particularly when measurement reliability, baseline performance, and the athletic characteristics of participants are considered.

The differences in muscular endurance may also reflect the influence of caffeine on exercise tolerance and perceived fatigue. Previous research has suggested that caffeine supplementation can influence exercise performance through mechanisms involving central stimulation and altered perception of effort (5). Tallis et al. (2022) emphasized the need for more context-specific caffeine research to clarify performance responses across exercise conditions and athletic populations (6). In the present study, plank holding duration increased in both groups, while the pre-exercise caffeine group demonstrated a more favorable post-intervention mean. However, plank performance may be influenced by several factors, including baseline muscular endurance, training adaptation, motivation, and test familiarization. Because these factors were not individually quantified, the observed between-group difference should not be interpreted as definitive evidence that caffeine timing independently improved muscular endurance.

Cardiorespiratory endurance was assessed using the Cooper 12-Minute Run Test, and both intervention groups demonstrated increased running distances following the intervention. The pre-exercise caffeine group achieved a greater post-intervention running distance than the mid-exercise caffeine group, with an unadjusted mean difference of 75.00 meters (95% CI: 2.95 to 147.05). This finding is compatible with the broader literature describing caffeine-related enhancement of endurance performance (4,5). Nevertheless, the relatively wide confidence interval indicates uncertainty regarding the magnitude of the between-group difference. Furthermore, improvements in running distance may reflect the combined influence of exercise training, supplementation, breathing practice, and repeated testing. Research on training-related performance adaptations in runners has demonstrated that structured exercise interventions can influence athletic performance (3). Accordingly, the changes observed in the present trial should be understood within the context of a multicomponent intervention rather than as isolated effects of caffeine administration.

Pranayama may have contributed to the improvements observed in both intervention groups through its potential influence on breathing regulation and respiratory functioning. Jerath et al. (2006) proposed physiological mechanisms through which slow, controlled breathing may influence autonomic nervous system activity and respiratory regulation (9). Similarly, Dhar et al. (2025) investigated a structured six-week pranayama intervention involving Bhastrika and Nadishodhana breathing techniques and reported changes in dynamic pulmonary function indices among young adults (10). These findings provide a rationale for incorporating breathing-based exercises into physical training programs. However, the present study did not directly assess pulmonary function, respiratory muscle strength, autonomic activity, or oxygen consumption. Furthermore, both intervention groups received pranayama, preventing an independent evaluation of its contribution to performance outcomes. Therefore, although pranayama may have provided a common complementary component, its specific physiological and performance-related effects cannot be determined from the current findings.

The combined use of caffeine and pranayama also raises the possibility of interactions between physiological stimulation, psychological responses, and breathing regulation. Coso et al. (2026) examined potential pharmacological and psychological influences of caffeine on exercise performance using a placebo-balanced approach, highlighting the importance of considering more than the pharmacological action of caffeine alone (8). Similarly, Vega-Muñoz et al. (2024), in a systematic review, examined placebo-related effects in caffeine supplementation during sport and exercise (13). These findings are relevant because participants who are aware of receiving caffeine may experience expectancy-related responses that influence performance. In the present study, outcome assessment and statistical analysis were reported as blinded; however, participant blinding was not described. Accordingly, expectancy effects cannot be excluded as an alternative or additional explanation for the observed differences. The findings therefore support further investigation of caffeine timing under controlled conditions rather than confirming a specific physiological interaction between caffeine and pranayama (11,12).

An important consideration is the distinction between the statistical significance and practical relevance of the observed differences. The unadjusted post-intervention comparisons yielded standardized effect sizes ranging from approximately 0.69 to 1.13 in absolute magnitude. However, these estimates were derived from post-intervention group differences rather than baseline-adjusted intervention effects. In addition, the study evaluated four performance outcomes without identifying a clearly prespecified primary endpoint. An exploratory Holm adjustment of the recalculated p-values retained statistical significance only for the hexagon agility comparison. This suggests that the evidence for consistent superiority across all four outcomes is less robust when multiple comparisons are considered. The clinical or competitive relevance of the observed differences also requires consideration of measurement reliability, participant training level, and established meaningful changes in athletic performance. Consequently, the findings should not be interpreted solely according to whether individual p-values were below 0.05 (13,14).

The results have potential implications for physiotherapists, sports scientists, athletic trainers, and recreational runners seeking practical strategies to optimize exercise performance. Pre-exercise caffeine ingestion may be worth investigating as a timing strategy when supplementation is combined with structured exercise and breathing practice. However, the findings do not establish a universally preferable caffeine-administration schedule, particularly because individual responses to supplementation can vary. Silva et al. (2025) emphasized the need to balance caffeine-related performance benefits against potential effects on sleep quality and recovery (15). Similarly, de Souza et al. (2022) reviewed the potential adverse effects associated with caffeine supplementation in sports settings, underscoring the importance of individual tolerance and safety considerations (16). Therefore, decisions regarding caffeine use should account for habitual intake, sensitivity, exercise timing, and potential adverse responses rather than relying exclusively on the observed performance differences in this small trial (17,18).

The study has several strengths, including its reported randomized design, equal allocation of participants between intervention groups, use of the same pranayama and running protocols, blinded outcome assessment, and assessment of multiple functional performance domains. The inclusion of muscular endurance, agility, sprint performance, and distance-running capacity allowed the comparison to extend beyond a single measure of athletic fitness. Nevertheless, several methodological limitations require consideration. The sample comprised only 36 healthy male runners recruited through convenience sampling, limiting the generalizability of the findings to female athletes, older individuals, elite runners, and populations with medical conditions. Although participants were randomly allocated, the groups differed in mean age by approximately five years, and the principal comparisons were not adjusted for baseline outcome values or age (19,20).The caffeine dose varied between 3 and 6 mg/kg, and individual dose exposure was not presented. Moreover, the intervention duration, detailed exercise and pranayama procedures, participant adherence, and exact timing of outcome assessments were insufficiently specified. The lack of a placebo or exercise-only comparison group also prevented independent determination of the

effects of caffeine and pranayama. Finally, participant-level paired-change variability, physiological measurements, and detailed safety outcomes were not provided, limiting the interpretation of intervention mechanisms and the precision of estimated changes (21,22).

Taken together, the findings indicate that pre-exercise caffeine ingestion combined with pranayama was associated with more favorable post-intervention physical performance than mid-exercise ingestion under the conditions examined. However, the evidence for superiority was strongest for agility, particularly after accounting for multiple outcome comparisons (23,24).The observed improvements in both groups also suggest that performance changes occurred during exposure to the combined intervention programs, without establishing the independent contribution of either caffeine or pranayama. Further adequately powered studies using standardized caffeine doses, clearly documented intervention protocols, prespecified outcomes, baseline-adjusted analyses, and appropriate control conditions would help clarify the influence of caffeine timing on athletic performance and determine whether the observed differences translate into meaningful advantages for runners (25).

Conclusion

The present study found that both pre-exercise and mid-exercise caffeine ingestion combined with supervised pranayama and running exercise were associated with improvements in muscular endurance, agility, sprint performance, and cardiorespiratory endurance among healthy male runners. Although the pre-exercise caffeine group demonstrated more favorable post-intervention performance across all four outcomes, the evidence for between-group superiority was most consistent for agility after consideration of multiple comparisons. These findings suggest that caffeine-ingestion timing may be relevant to exercise-performance outcomes; however, the small sample size, baseline differences, and reliance on unadjusted analyses limit definitive conclusions regarding comparative effectiveness.

DECLARATIONS

Author Contributions:	Concept: HA, LA; Design: HA, LA, MN; Data Collection: LA, HI; Analysis: HA, MN; Drafting: HA, LA, HI.
Ethical Approval:	Ethical approval was obtained from Superior university Lahore Pakistan.
Informed Consent:	Written informed consent was obtained from parents or guardians before participant enrolment. Trial Registration: ClinicalTrials.gov registration: NCT05392296.
Conflict of Interest:	The authors declare no conflict of interest.
Funding:	No external funding was received for this study.
Data Availability:	Data are available from the corresponding author on reasonable request.
Acknowledgments:	None.
AI Declaration:	Generative AI tools were used solely for language and grammatical refinement. The authors verified the final manuscript and remain fully responsible for its accuracy, integrity, and scientific content.

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