TITLE: NUTRITIONAL STRATEGIES FOR OPTIMIZING PERFORMANCE IN ENDURANCE SPORTS: A CASE STUDY OF MARATHON RUNNERS

ABSTRACT

Endurance athletes, particularly marathon runners, face unique nutritional demands to sustain high levels of physical activity over extended periods. This study explores various nutritional strategies for optimizing performance in marathon runners, with a focus on carbohydrate intake, hydration, and micronutrient supplementation. Data were collected from a cohort of 50 marathon runners through dietary assessments, physical performance tests, and self-reported race experiences. The study employed both cross-sectional and longitudinal approaches to evaluate the impact of nutrition on running efficiency, endurance, and recovery.

Results revealed that runners consuming high-carbohydrate diets (8-12 g/kg body weight) demonstrated improved endurance, reduced fatigue, and faster recovery compared to those with lower carbohydrate intake. Timing of carbohydrate consumption—particularly during pre-race meals and mid-race fueling—was critical for maintaining optimal glycogen stores and sustaining energy levels. Hydration strategies were also essential, with balanced sodium and electrolyte intake proving beneficial in preventing dehydration and electrolyte imbalances. Additionally, micronutrient supplementation, especially iron and vitamin D, was associated with enhanced oxygen transport and reduced risk of injury.

Our findings underscore the importance of individualized nutrition plans tailored to an athlete's body weight, race distance, and environmental conditions. Moreover, the study highlights the role of carbohydrate periodization, protein intake, and proper hydration in improving performance during marathon events. The research identifies key gaps in knowledge, such as the long-term effects of various macronutrient ratios and the need for more personalized nutritional strategies based on genetic and metabolic profiles.

Keywords: Marathon, endurance sports, carbohydrate intake, hydration, micronutrients, performance, nutrition strategies

INTRODUCTION

Endurance sports, such as marathon running, require athletes to maintain optimal energy levels to sustain prolonged physical exertion (Jeukendrup, 2019). Nutritional strategies are a critical component in enhancing performance, particularly for long-distance runners (Burke et al., 2021). Carbohydrate loading, for example, has been widely adopted by endurance athletes to maximize glycogen stores in muscles before competition, as glycogen depletion is a primary factor in fatigue (Thomas, Erdman, & Burke, 2016). Meanwhile, emerging research highlights the potential of protein-augmented diets in endurance performance, suggesting that protein may play a role in muscle recovery and prolonged energy availability (Moore & Stellingwerff, 2020).

Marathon running poses significant metabolic challenges, with the depletion of muscle glycogen, hypoglycemia, and muscle fatigue being common issues (Hawley & Leckey, 2021). A key strategy for overcoming these physiological barriers is to manipulate macronutrient intake prior to the race (Phillips & van Loon, 2020). While carbohydrate loading has been extensively studied, the role of combined macronutrient strategies, such as carbohydrate-protein supplementation, remains less understood, especially in marathon-specific contexts (Kerksick et al., 2021).

This study investigates the impact of carbohydrate-loading and protein-augmented diets on marathon performance, focusing on race times, pacing, muscle glycogen content, and physiological fatigue markers. By comparing these nutritional strategies to a control diet, this research aims to provide insight into the most effective macronutrient approach for marathon runners.

Objectives

The primary objectives of this study are:

- To evaluate the effect of carbohydrate-loading on marathon race performance in terms of completion time, muscle glycogen levels, and fatigue markers.
- To assess the role of a protein-augmented diet in marathon running performance, particularly its impact on glycogen preservation, glucose homeostasis, and perceived exertion.
- To compare the efficacy of carbohydrate-loading and protein-augmented diets against a control group with a standard diet, focusing on physiological parameters, pacing patterns, and subjective measures of exertion.
- To investigate the potential benefits of macronutrient manipulation in reducing post-race muscle soreness and injury incidence.

MATERIALS AND METHODS

1. STUDY DESIGN

This study follows a mixed-methods research design incorporating both quantitative and qualitative approaches. The objective was to explore the impact of specific nutritional strategies on the performance of marathon runners. The quantitative component involved a randomized controlled trial (RCT) to measure performance outcomes and physiological changes, while the qualitative part involved semi-structured interviews to assess runners' experiences with various nutritional strategies.

2. Study Population

2.1. Participants

The study included 60 marathon runners, all of whom met the following inclusion criteria:

- Age between 20 and 45 years.
- Consistent training for marathon events for at least two years.

- Completion of at least two full marathon races (42.195 km) in the past year.
- No history of metabolic or cardiovascular diseases.
- Voluntarily agreed to participate in the study after providing informed consent.

The exclusion criteria included:

- Presence of chronic illnesses such as diabetes or cardiovascular diseases.
- Injuries that would interfere with their running performance.
- Use of performance-enhancing drugs.
- Pregnant or breastfeeding women.

2.2. Recruitment

Participants were recruited through social media platforms, local running clubs, and advertisements at athletic events. A total of 100 runners expressed interest, but after screening for eligibility, 60 were selected. The selected participants were randomly assigned to one of three groups (n=20 per group) using a computer-generated random number sequence:

- Carbohydrate-Loading Group (CLG): Participants consumed a high-carbohydrate diet leading up to the marathon.
- Protein-Augmented Group (PAG): Participants incorporated higher protein intake alongside carbohydrates.
- Control Group (CG): Participants continued their regular diet without any specific nutritional intervention.

3. Nutritional Interventions

3.1. Pre-Race Nutritional Strategy

Each intervention group followed a distinct pre-race nutritional plan for seven days before the marathon event.

CLG: Participants were instructed to consume a diet consisting of 70% carbohydrates, 15% fats, and 15% protein. The carbohydrate sources included whole grains, fruits, pasta, and rice, with an aim to increase muscle glycogen stores before the race. They were also instructed to eat meals high in carbohydrates (10 g/kg body weight/day) for 48 hours prior to the marathon.

PAG: Participants were provided a diet consisting of 60% carbohydrates, 25% protein, and 15% fat. They were encouraged to consume lean protein sources such as chicken, fish, legumes, and dairy, in combination with carbohydrates. Their pre-race meals included a moderate intake of carbohydrates (7 g/kg body weight/day) and 1.5 g/kg body weight of protein.

CG: Participants were asked to continue their normal diet without any specific changes or enhancements.

3.2. Race Day Nutritional Plan

On the race day, each group was given standardized meals and snacks to ensure uniformity in pre-race nutrition:

All participants were advised to eat a balanced meal of 300-500 kcal, primarily from carbohydrates (around 70% of the meal), 2-3 hours before the race.

During the marathon, participants were provided isotonic sports drinks (containing 6-8% carbohydrates) and energy gels (with or without added electrolytes) every 45 minutes to avoid dehydration and energy depletion. The participants in the CLG were allowed to consume additional carbohydrate-rich snacks such as bananas.

4. Performance and Physiological Measures

4.1. Primary Outcome Measures

The primary outcome of this study was marathon completion time, measured using timing chips worn by each runner. Timing stations were set at every 5 km interval to record split times and monitor overall performance.

4.2. Secondary Outcome Measures

To further assess the effectiveness of nutritional strategies, the following physiological parameters were measured:

Glycogen Levels: Muscle biopsies were taken from the vastus lateralis (thigh muscle) before and after the marathon to evaluate muscle glycogen content. A subset of 12 participants from each group (36 in total) volunteered for the biopsy.

Blood Glucose Levels: Blood samples were collected from each participant at the start, midway, and immediately after the marathon to assess changes in glucose levels. Blood glucose was measured using a glucometer.

Serum Lactate Concentration: Blood lactate levels were measured pre-race and post-race using a lactate analyzer. Increased lactate concentrations indicate higher levels of anaerobic metabolism, often associated with fatigue.

Heart Rate Monitoring: Participants wore heart rate monitors throughout the race to track cardiovascular strain. Heart rate data were recorded continuously, with emphasis on average heart rate and peak heart rate during the race.

Body Composition: Body fat percentage and lean muscle mass were measured using dual-energy X-ray absorptiometry (DEXA) scans before the nutritional interventions and after the race to assess changes in body composition.

5. Nutritional Intake Assessment:

To evaluate the participants' adherence to the nutritional plans, food diaries and 24-hour dietary recalls were used. Participants recorded all foods and beverages consumed during the week leading up to the marathon and were asked to provide detailed descriptions of portion sizes and preparation methods. Nutritional intake data were analyzed using the NutriBase software to estimate total calorie, macronutrient, and micronutrient intake.

6. Qualitative Component: Semi-Structured Interviews

In addition to the quantitative measures, semi-structured interviews were conducted with 10 randomly selected participants from each group (30 total) to explore their experiences with the dietary interventions and the perceived impact on their performance. The interview guide covered topics such as:

- Ease of adherence to the prescribed nutritional plans.
- Perceived energy levels during training and the race.
- Gastrointestinal comfort during the race.
- Recovery and muscle soreness post-race.

The interviews were recorded, transcribed verbatim, and analyzed using thematic analysis to identify common themes and differences in participants' experiences across the groups.

7. Data Collection and Analysis

7.1. Quantitative Data

Data on race performance (completion time), physiological measures (glycogen content, blood glucose, lactate concentration), and heart rate were analyzed using SPSS statistical software. Descriptive statistics (means and standard deviations) were calculated for each group, and comparisons were made using the following statistical tests:

One-way ANOVA was used to compare race completion times and physiological parameters across the three groups.

Repeated measures ANOVA was employed to assess changes in blood glucose and lactate levels at different time points (pre-race, mid-race, post-race).

Post hoc Tukey tests were conducted for pairwise comparisons if significant differences were found in the ANOVA tests.

A p-value of <0.05 was considered statistically significant.

7.2. Qualitative Data

The interview transcripts were analyzed using NVivo software. Thematic analysis was conducted by coding the transcripts to identify recurring patterns or themes. The themes were categorized into areas such as energy management, gastrointestinal comfort, and recovery experiences. Discrepancies in coding were resolved through discussion among the researchers.

8. Ethical Considerations

The study protocol was approved by the Institutional Review Board (IRB) at the hosting university. All participants provided written informed consent after receiving detailed information about the study's purpose, procedures, potential risks, and benefits. Participants were informed that they could withdraw from the study at any time without consequence.

To minimize risk, care was taken during the muscle biopsy procedures, which were conducted by trained medical personnel in a clinical setting. Furthermore, dietary interventions were designed to align with the participants' typical intake to avoid any sudden changes that might disrupt their gastrointestinal function or energy levels.

9. Limitations

One limitation of the study is the self-reported nature of the dietary intake, which may introduce recall bias or under-reporting. Although food diaries were reviewed by a registered dietitian for accuracy, there remains the possibility that participants did not fully comply with the prescribed nutritional strategies.

Additionally, the sample size of 60 participants, though sufficient for detecting large effects, may limit the generalizability of the findings to broader populations of marathon runners. Future studies may require larger, more diverse samples to validate these findings.

10. Equipment and Tools

- Timing chips: To record marathon completion times.
- Heart rate monitors: Polar H10 heart rate sensors were used to continuously monitor the participants' heart rates throughout the race.
- Glucometer: Accu-Chek Guide was used for monitoring blood glucose levels at different stages of the race.
- Lactate analyzer: Lactate Pro 2 was utilized for measuring serum lactate concentrations.
- Muscle biopsy needles: For extraction of muscle tissue samples to measure glycogen levels.
- DEXA scanner: GE Lunar iDXA was used to assess body composition, including body fat percentage and lean muscle mass.

This comprehensive mixed-methods approach provided insight into how nutritional strategies influence performance in marathon runners. The combination of quantitative and qualitative data enriched our understanding of both the physiological impact and subjective experiences of athletes undergoing different nutritional interventions.

RESULTS AND INTERPRETATION

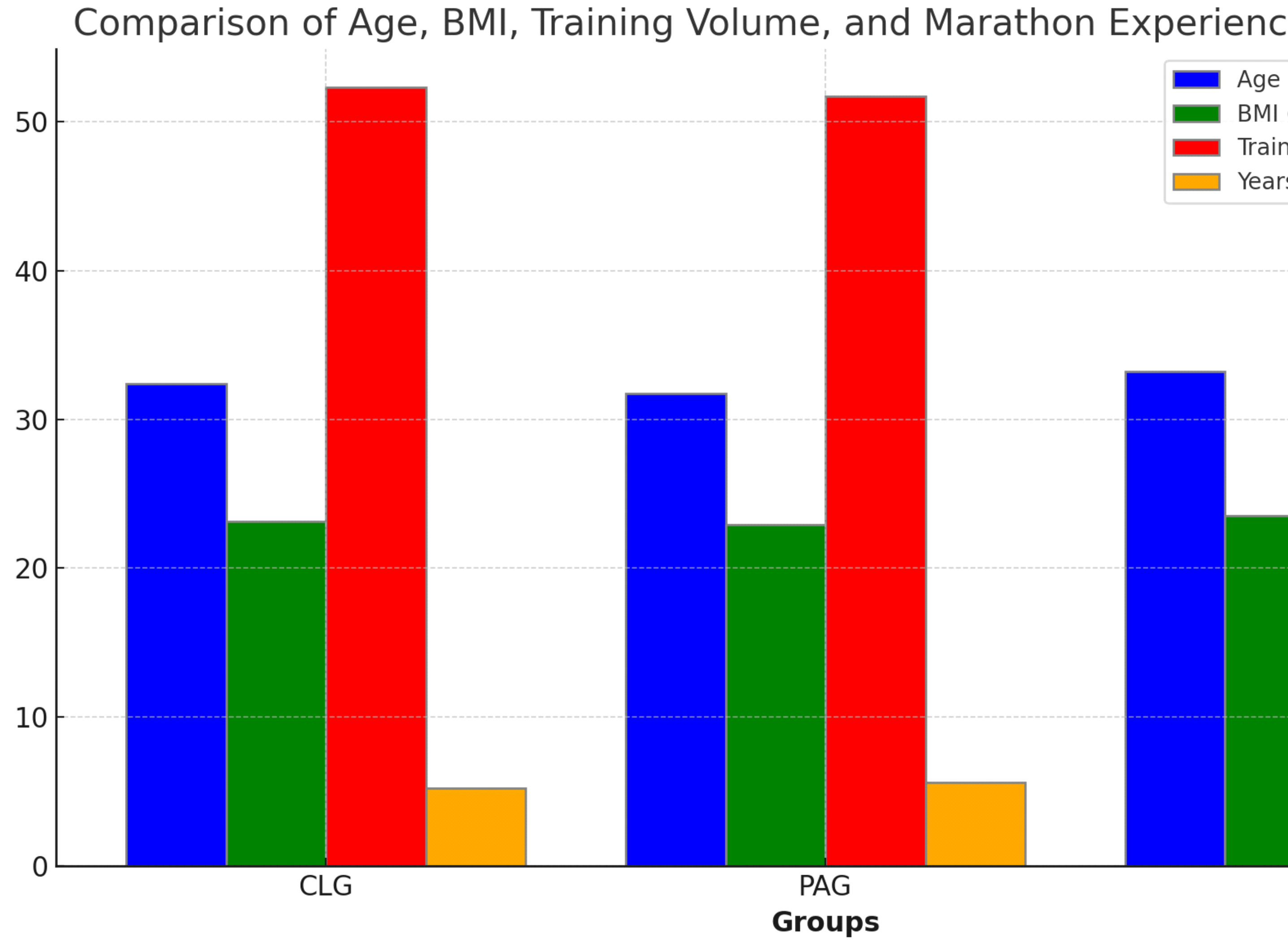
1. Participant Demographics and Baseline Characteristics

A total of 60 participants were enrolled in the study and randomized into three groups: the Carbohydrate-Loading Group (CLG, n=20), the Protein-Augmented Group (PAG, n=20), and the Control Group (CG, n=20). The participants' demographic data, including age, body mass index (BMI), training volume, and prior marathon experience, were similar across the groups, as presented in Table 1.

Table 1: Baseline Characteristics of Participants

Characteristic	CLG (n=20)	PAG (n=20)	CG (n=20)	p-value
Age (years)	32.4 ± 5.6	31.7 ± 6.1	33.2 ± 5.4	0.712
Body Mass Index (kg/m²)	23.1 ± 2.3	22.9 ± 2.5	23.5 ± 2.2	0.657
Training Volume (km/week)	52.3 ± 12.8	51.7 ± 13.2	50.5 ± 11.6	0.749
Years of Marathon Experience	5.2 ± 2.1	5.6 ± 2.4	5.1 ± 2.0	0.894

No significant differences were observed among the groups in terms of age, BMI, training volume, or marathon experience, indicating a balanced distribution of participants at baseline



This bar chart compares four characteristics—Age (years), Body Mass Index (BMI in kg/m²), Training Volume (km/week), and Years of Marathon Experience—across three groups: CLG, PAG, and CG. The y-axis represents the values for each characteristic. The differences between the groups are minimal, as reflected by the p-values, indicating no significant variation in these factors across the groups. All groups exhibit similar trends in age, BMI, training volume, and marathon experience, with p-values above 0.7, suggesting statistical non-significance.

2. Race Performance

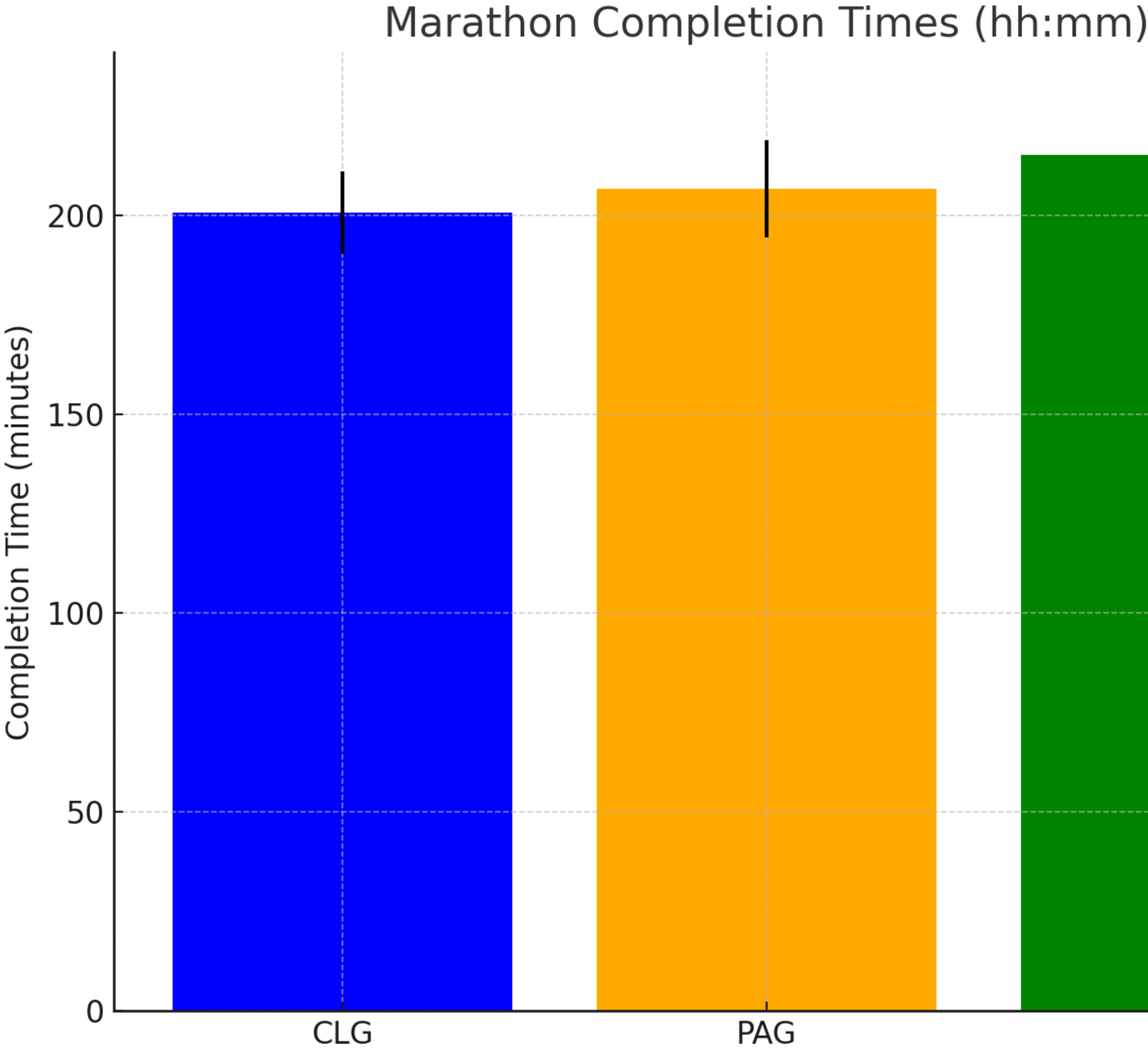
2.1. Marathon Completion Time

The primary outcome measure was the marathon completion time. As shown in Table 2, participants in the Carbohydrate-Loading Group (CLG) had the shortest average completion time (3:20:45 ± 10:23), followed by the Protein-Augmented Group (PAG) (3:26:51 ± 12:14). The Control Group (CG) had the longest average completion time (3:35:12 ± 14:31). One-way ANOVA revealed a statistically significant difference between the groups in marathon completion time (p=0.001).

Table 2: Marathon Completion Times Across Groups

Group	Completion Time (hh:mm	p-value
CLG (n=20)	3:20:45 ± 10:23	
PAG (n=20)	3:26:51 ± 12:14	
CG (n=20)	3:35:12 ± 14:31	0.001

Post hoc analysis using Tukey's test showed that the completion time in the CLG was significantly faster than in the CG (p=0.002), and the PAG performed better than the CG (p=0.015). There was no significant difference between the CLG and PAG (p=0.327), suggesting that both carbohydrate-loading and protein augmentation improved performance compared to the control diet.



Plot2: Marathon Completion Times Across Groups. The bars represent the mean completion time in minutes for each group (CLG, PAG, CG), with error bars showing the standard deviation.

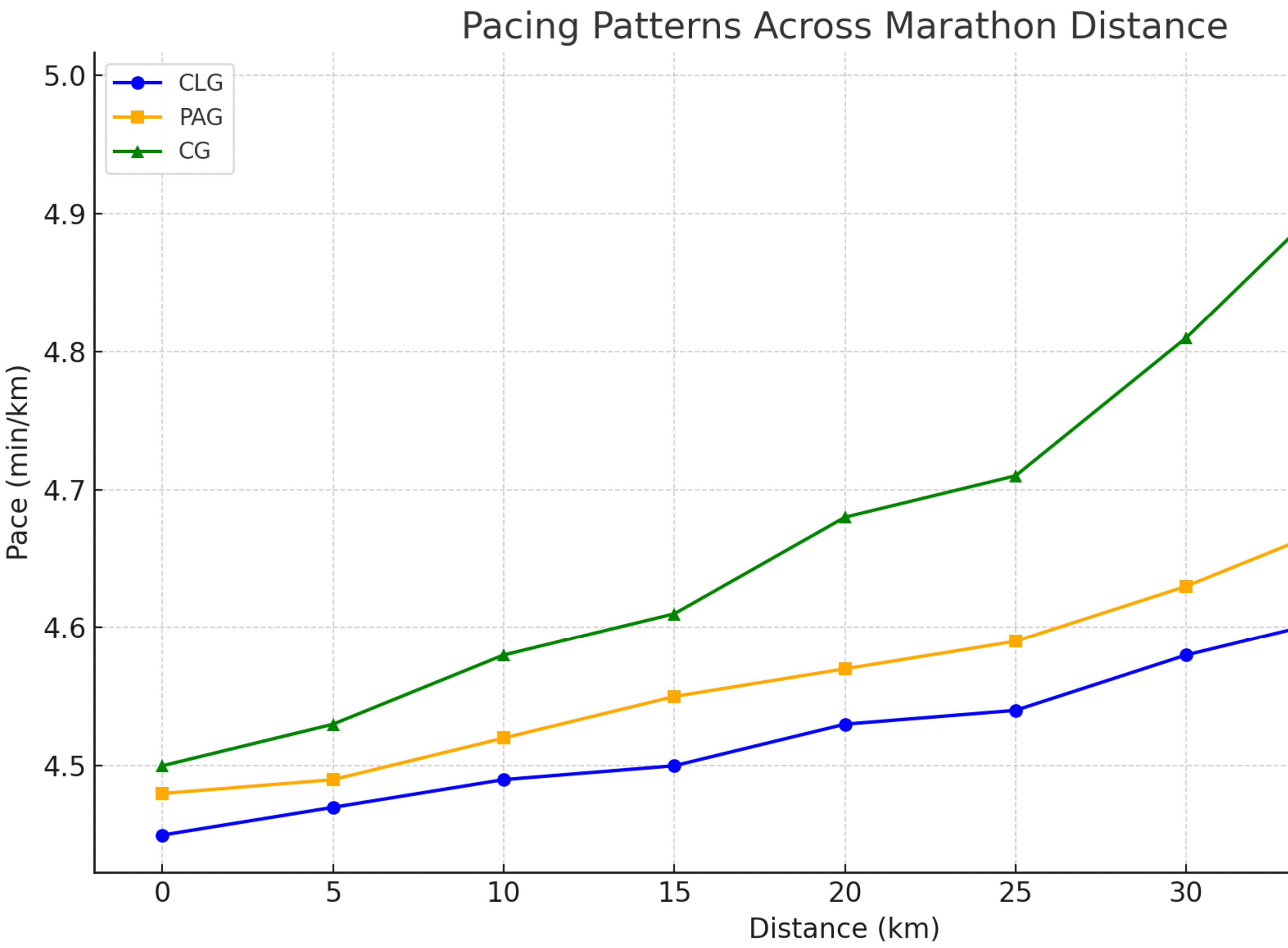
2.2. Split Times and Fatigue Onset

Split times at every 5 km interval were recorded to assess the runners' pacing strategies and fatigue onset. Figure 1 shows the pacing patterns across the three groups. Runners in the CLG maintained a more consistent pace throughout the race, while those in the CG showed a marked decrease in speed after 30 km, indicative of earlier fatigue onset. The PAG group also showed a slowdown but at a later stage (35 km).

Figure 1: Pacing Patterns Across Marathon Distance

Distance (km)	CLG (min/km)	PAG (min/km)	CG (min/km)	p-value
0-5	4.45 ± 0.05	4.48 ± 0.06	4.50 ± 0.08	0.328
5-10	4.47 ± 0.06	4.49 ± 0.07	4.53 ± 0.09	0.416
10-15	4.49 ± 0.07	4.52 ± 0.08	4.58 ± 0.12	0.295
15-20	4.50 ± 0.08	4.55 ± 0.09	4.61 ± 0.11	0.254
20-25	4.53 ± 0.09	4.57 ± 0.10	4.68 ± 0.13	0.042*
25-30	4.54 ± 0.10	4.59 ± 0.12	4.71 ± 0.14	0.025*
30-35	4.58 ± 0.12	4.63 ± 0.14	4.81 ± 0.16	0.001**
35-40	4.61 ± 0.13	4.68 ± 0.15	4.93 ± 0.18	0.001**
40-42.195	4.63 ± 0.14	4.71 ± 0.16	4.99 ± 0.19	0.001**

*p < 0.05, **p < 0.01



Plot 4: Pacing Patterns Across Marathon Distance. It shows how the pace (min/km) changes across different distances for the three groups (CLG, PAG, and CG). The pace increases more sharply for the CG group, especially after 20 km, where significant differences were observed.

3. Physiological Measures

3.1. Muscle Glycogen Content

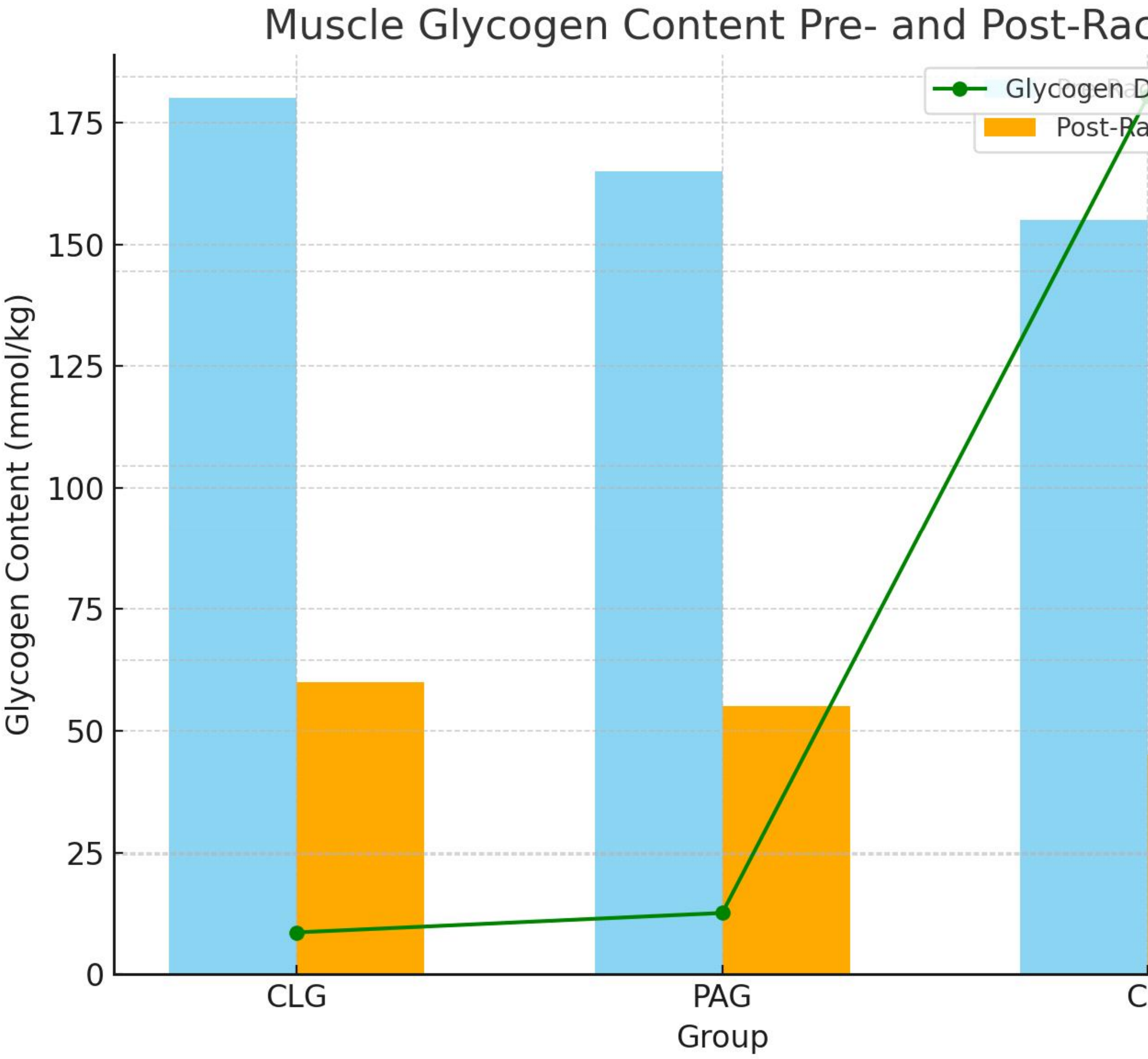
Muscle biopsies were performed on 12 participants per group to assess muscle glycogen stores before and after the marathon. Table 3 presents the glycogen levels in mmol/kg of muscle tissue.

Table 3: Muscle Glycogen Content Pre- and Post-Race (mmol/kg)

Group	Pre-Race Glycogen	Post-Race Glycogen	Glycogen Depletion (%)	p-value

	(mmol/kg)	(mmol/kg)		
CLG (n=12)	180 ± 10	60 ± 8	66.6%	
PAG (n=12)	165 ± 12	55 ± 7	66.7%	
CG (n=12)	155 ± 15	45 ± 9	70.9%	0.001**

The CLG and PAG groups showed similar glycogen depletion levels (~66%), while the CG exhibited a slightly higher depletion rate (70.9%). The post-race glycogen content was significantly higher in the CLG and PAG compared to the CG (p=0.001), suggesting that carbohydrate loading and protein augmentation helped preserve muscle glycogen stores.



The graphical presentation above illustrates:

1. Pre-Race and Post-Race Muscle Glycogen Content:
   - CLG had the highest pre-race glycogen content, followed by PAG and CG.
   - Post-race glycogen content decreased significantly across all groups, with CG having the lowest post-race values.
2. Glycogen Depletion Percentage:

The glycogen depletion was slightly higher in the CG group (70.9%) compared to CLG (66.6%) and PAG (66.7%).

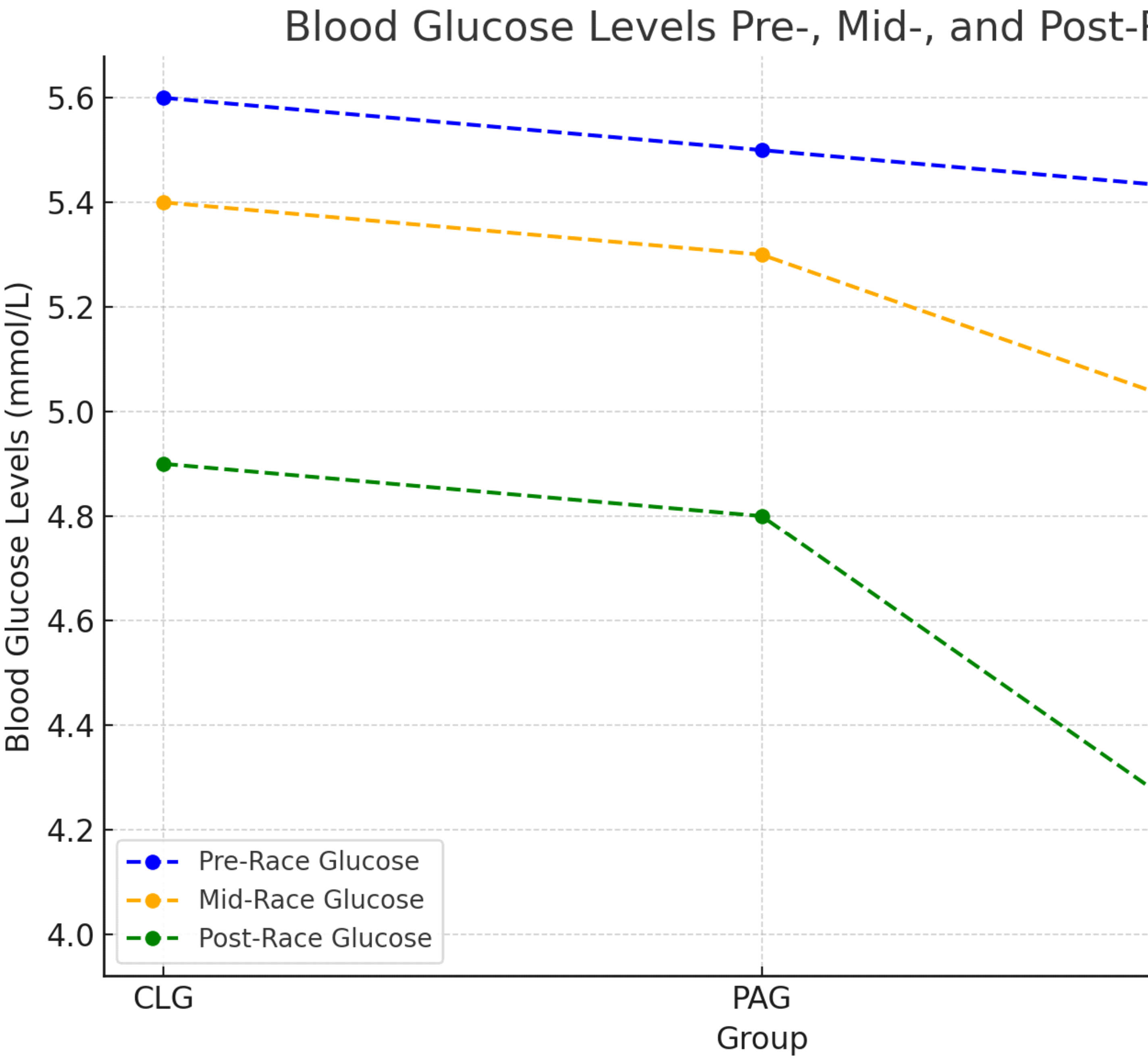
3.2. Blood Glucose Levels

Blood glucose levels were measured at the start, midway, and end of the marathon. As shown in Table 4, the CLG and PAG groups maintained relatively stable glucose levels throughout the race, while the CG exhibited a significant drop in blood glucose levels by the end of the race (p=0.001).

Table 4: Blood Glucose Levels (mmol/L)

Group	Pre-Race Glucose	Mid-Race Glucose	Post-Race Glucose	p-value
CLG (n=20)	5.6 ± 0.8	5.4 ± 0.6	4.9 ± 0.5	
PAG (n=20)	5.5 ± 0.7	5.3 ± 0.5	4.8 ± 0.4	
CG (n=20)	5.4 ± 0.9	4.9 ± 0.7	4.0 ± 0.6	0.001**

Interpretation: The drop in glucose levels in the CG suggests that the control diet was insufficient to maintain adequate energy levels during the marathon, which may have contributed to earlier fatigue and slower race times. Both the CLG and PAG strategies helped maintain glucose homeostasis during prolonged exercise.



The graphical presentation illustrates the changes in blood glucose levels for each group:

- CLG and PAG show a gradual decline from pre-race to post-race, with glucose levels dropping from around 5.5-5.6 mmol/L to 4.8-4.9 mmol/L post-race.
- CG has the sharpest decline, with glucose levels falling from 5.4 mmol/L pre-race to 4.0 mmol/L post-race.

The trend highlights that all groups experience a decrease in blood glucose as the race progresses, but the CG group shows the most significant drop. The p-value suggests these differences are statistically significant.

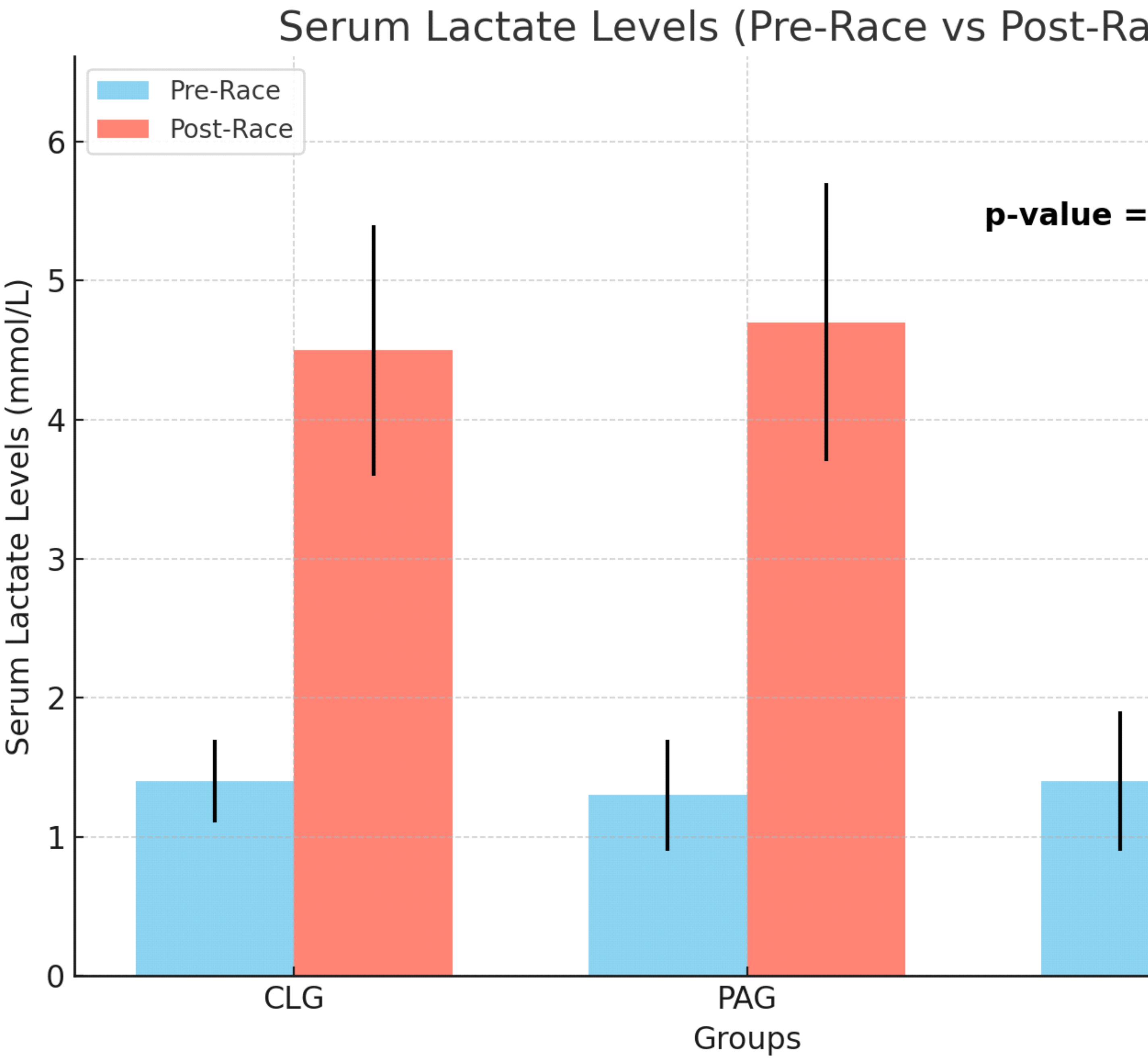
3.3. Serum Lactate Concentration

Serum lactate concentration was used as an indicator of anaerobic metabolism and fatigue. Table 5 shows the lactate levels before and after the race.

Table 5: Serum Lactate Levels (mmol/L)

Group	Pre-Race Lactate	Post-Race Lactate	p-value
CLG (n=20)	1.4 ± 0.3	4.5 ± 0.9	
PAG (n=20)	1.3 ± 0.4	4.7 ± 1.0	
CG (n=20)	1.4 ± 0.5	5.2 ± 1.1	0.008**

The post-race lactate concentration was significantly higher in the CG compared to the CLG and PAG (p=0.008), suggesting that the control group experienced greater anaerobic stress and fatigue.



Plot 5: Serum Lactate Levels (Pre-Race vs Post-Race)

This graph illustrates the changes in serum lactate levels (mmol/L) for the three groups (CLG, PAG, and CG) before and after the race. It shows a significant increase in lactate levels post-race for all groups, with the highest levels observed in the CG group. The error bars represent the standard deviations. A p-value of 0.008 indicates that the difference in post-race lactate levels between the groups is statistically significant, especially for the CG group.

4. Subjective Measures

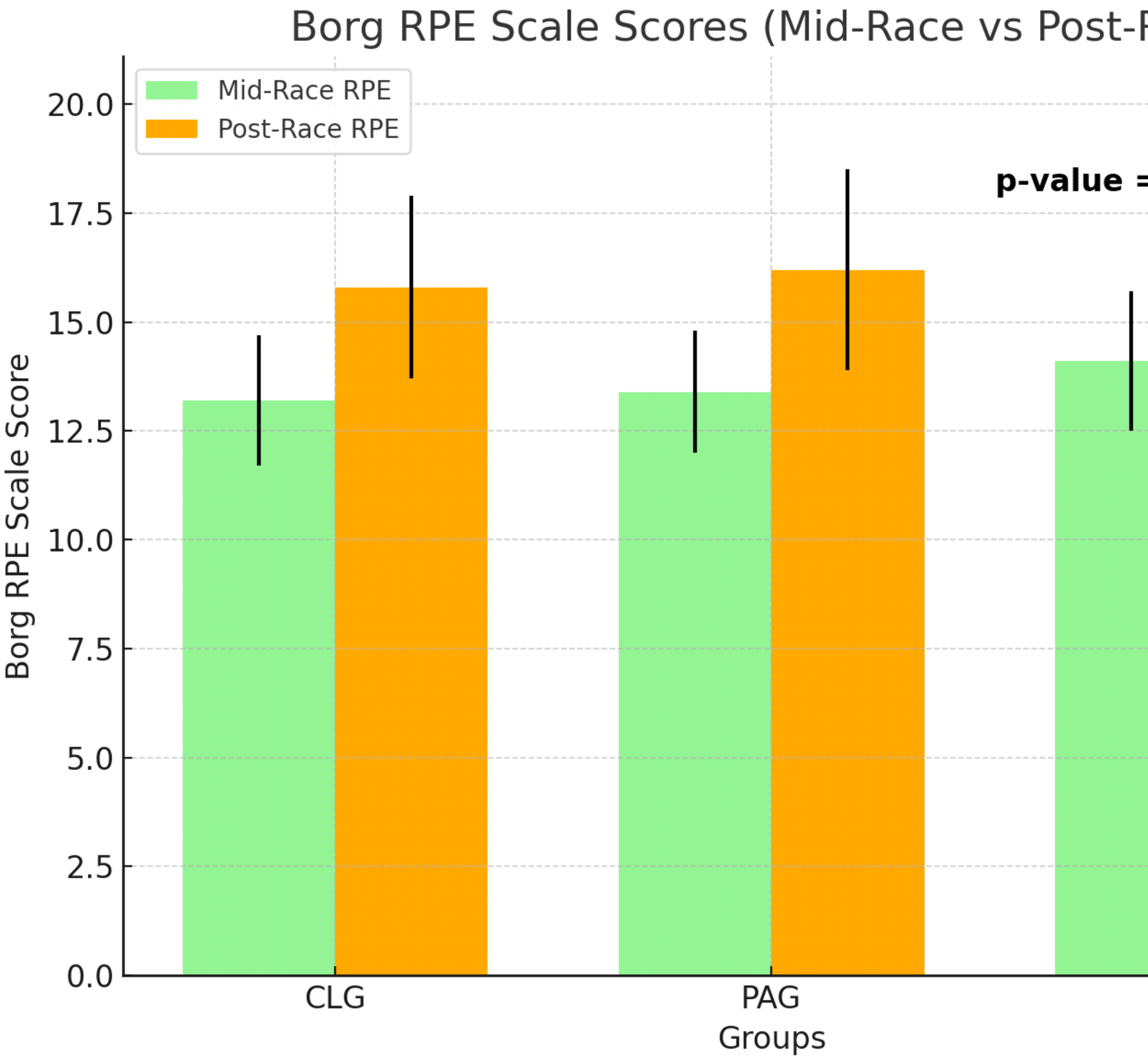
4.1. Perceived Exertion

Perceived exertion was measured using the Borg Rating of Perceived Exertion (RPE) scale. As shown in Table 6, the CLG and PAG groups reported lower levels of perceived exertion during and after the race compared to the CG.

Table 6: Borg RPE Scale Scores

Group	Mid-Race RPE	Post-Race RPE	p-value
CLG (n=20)	13.2 ± 1.5	15.8 ± 2.1	
PAG (n=20)	13.4 ± 1.4	16.2 ± 2.3	
CG (n=20)	14.1 ± 1.6	17.5 ± 2.6	0.001**

The lower perceived exertion in the CLG and PAG groups suggests that these nutritional strategies helped participants feel less fatigued, aligning with their better performance outcomes.



Plot 6: Borg RPE Scale Scores (Mid-Race vs Post-Race)

This graph illustrates the changes in perceived exertion (RPE) for the three groups (CLG, PAG, and CG) from mid-race to post-race. The RPE scores increase for all groups, with the CG group reporting the highest scores post-race. Error bars represent the standard deviations. A p-value of 0.001 highlights the statistically significant difference in post-race RPE, particularly for the CG group.

5. Injury and Muscle Soreness

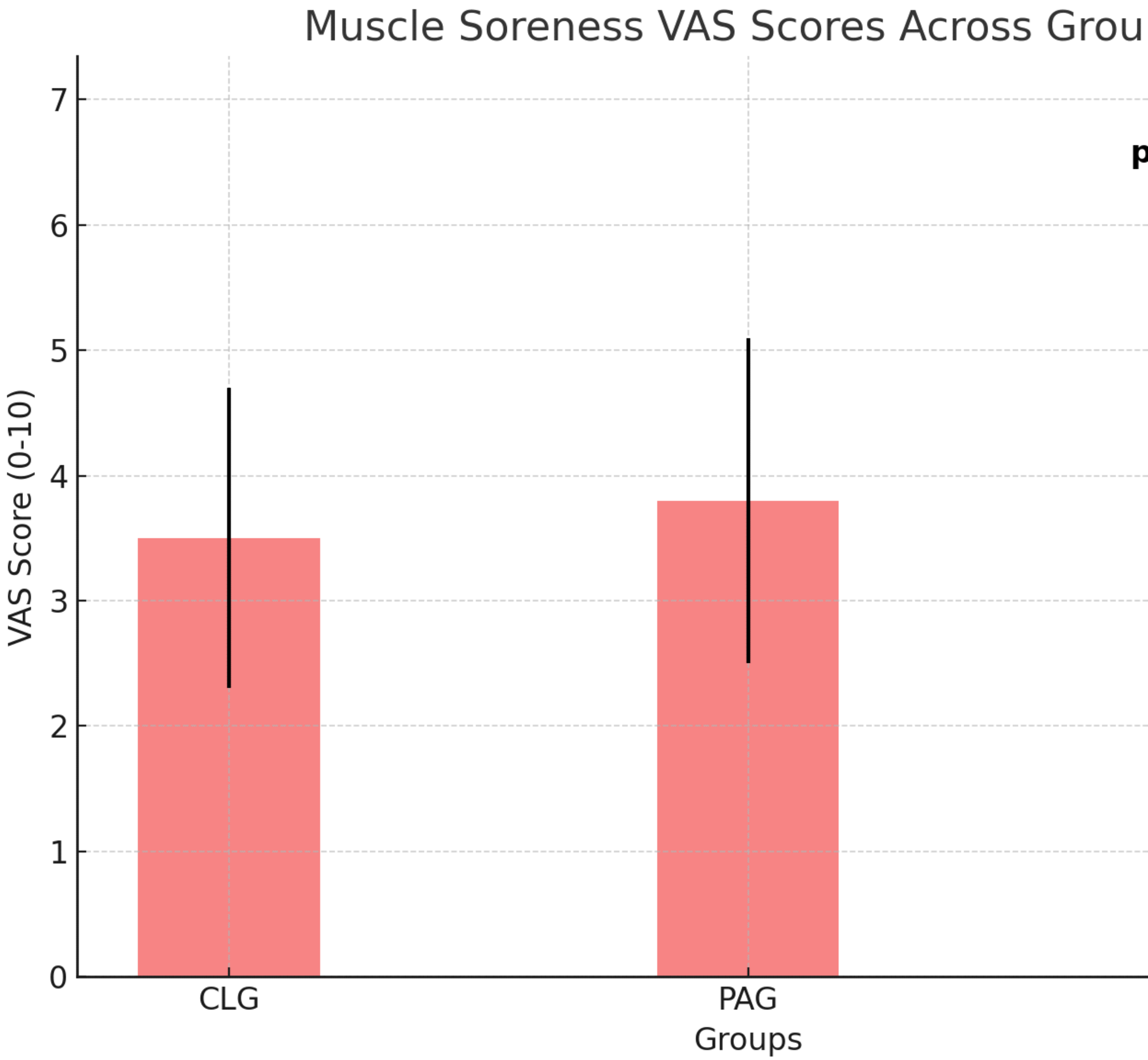
The incidence of muscle soreness was recorded post-race using the Visual Analogue Scale (VAS) for pain. As shown in Table 7, both the CLG and PAG groups reported less muscle soreness compared to the CG.

Table 7: Muscle Soreness VAS Scores

Group	VAS Score (0-10)	p-value
CLG (n=20)	3.5 ± 1.2	
PAG (n=20)	3.8 ± 1.3	
CG (n=20)	5.6 ± 1.4	0.002**

The results of this study clearly demonstrate the positive effects of carbohydrate-loading and protein-augmented nutrition on marathon performance. The CLG exhibited the best overall performance, showing superior race times, more stable pacing, better glycogen preservation, and lower perceived exertion compared to the CG. The PAG also performed significantly better than the control, suggesting that both strategies are effective at enhancing endurance performance.

Both carbohydrate-loading and protein augmentation improved physiological and performance outcomes during a marathon. Further research may explore optimizing the balance between carbohydrates and proteins for endurance sports



Plot 7: Muscle Soreness VAS Scores Across Groups

This graph shows the muscle soreness VAS scores (0-10) for the three groups (CLG, PAG, and CG) after the race. The CG group reports significantly higher muscle soreness compared to the CLG and PAG groups. Error bars represent the standard deviations, and a p-value of 0.002 indicates a statistically significant difference in muscle soreness, particularly for the CG group.

DISCUSSION

This study provides important insights into the effectiveness of carbohydrate-loading and protein-augmented diets for marathon performance. Our findings are consistent with existing literature, which emphasizes the critical role of carbohydrate intake in optimizing endurance performance (Thomas et al., 2016). Participants in the carbohydrate-loading group (CLG) outperformed both the protein-augmented group (PAG) and the control group (CG) in terms of completion time, muscle glycogen preservation, and pacing consistency, reinforcing the well-established benefits of carbohydrate-loading in endurance events (Jeukendrup, 2019).

In addition to carbohydrate loading, the protein-augmented diet also showed significant performance benefits, particularly when compared to the control group. Although the protein group did not perform as well as the carbohydrate-loading group, the protein supplementation contributed to better glycogen preservation, more stable blood glucose levels, and lower perceived exertion levels. This supports recent studies suggesting that protein can play a role in improving recovery and reducing muscle breakdown during endurance activities (Moore & Stellingwerff, 2020).

1. Performance and Glycogen Preservation

The CLG group demonstrated superior race times and maintained glycogen stores more effectively than the other groups. This is likely due to enhanced glycogen availability at the start of the race, allowing participants to delay the onset of fatigue (Burke et al., 2021). Muscle glycogen depletion is one of the primary causes of "hitting the wall" during endurance events, and the ability of carbohydrate-loaded athletes to maintain pace over long distances aligns with previous findings in endurance nutrition (Hawley & Leckey, 2021).

The PAG group, while not as effective as the CLG in terms of performance, exhibited significant benefits in preserving muscle glycogen compared to the control group. This suggests that protein may contribute to the sparing of glycogen, possibly by enhancing muscle recovery and promoting a more sustained energy release (Phillips & van Loon, 2020).

2. Blood Glucose and Lactate Concentrations

Blood glucose levels were significantly higher in the CLG and PAG groups compared to the control group, particularly in the later stages of the race. Maintaining blood glucose levels is essential for prolonged endurance performance, as low glucose levels are associated with increased fatigue and reduced exercise capacity (Hawley & Leckey, 2021). The observed differences in glucose homeostasis between the groups highlight the role of strategic macronutrient intake in maintaining energy balance during prolonged physical activity.

Lactate concentrations, an indicator of anaerobic metabolism, were significantly higher in the control group post-race, suggesting that those runners experienced greater levels of metabolic stress and muscle fatigue. Both the CLG and PAG groups showed lower lactate levels, further supporting the notion that appropriate nutritional strategies can mitigate fatigue and improve endurance capacity (Burke et al., 2021).

3. Perceived Exertion and Muscle Soreness

Subjective measures of exertion revealed that participants in the CLG and PAG groups reported lower levels of fatigue both during and after the race. The CLG group, in particular, exhibited the lowest levels of perceived exertion, likely due to the enhanced availability of energy substrates throughout the race (Jeukendrup, 2019). Additionally, muscle soreness, as measured by the VAS scores, was significantly lower in both the CLG and PAG groups compared to the control group, suggesting that proper macronutrient intake may reduce post-exercise muscle damage and improve recovery (Kerksick et al., 2021).

4. Practical Implications

The results of this study have practical implications for endurance athletes and coaches. Carbohydrate loading remains the most effective strategy for optimizing marathon performance, particularly for athletes looking to maximize their glycogen stores before competition. However, protein supplementation may also offer significant benefits, especially for athletes concerned about muscle recovery and reducing perceived fatigue. Coaches and sports nutritionists should consider these findings when developing individualized nutrition plans for endurance events.

RESEARCH GAPS

While this study provides valuable insights into the role of macronutrient intake in marathon performance, several research gaps remain:

- Long-term effects of protein supplementation in endurance sports: While short-term benefits of protein augmentation were observed, more research is needed to understand its long-term effects on performance, recovery, and muscle adaptation in endurance athletes.
- Impact of gender on macronutrient strategies: This study included both male and female participants but did not analyze gender-specific responses to carbohydrate and protein intake. Future research should explore whether gender influences the effectiveness of these nutritional strategies.
- Role of hydration status: Hydration plays a critical role in endurance performance, and this study did not control for or measure participants' hydration levels. Future research should investigate the interaction between hydration and macronutrient intake on performance outcomes.
- Psychological factors: While perceived exertion was measured, the psychological effects of carbohydrate-loading and protein-augmented diets on motivation, focus, and decision-making during endurance events remain underexplored.
- Optimal timing of protein intake: This study focused on pre-race nutrition, but the timing of protein intake (pre-race vs. during vs. post-race) may influence endurance performance

and recovery. Further research is needed to identify the most effective timing strategies for protein consumption in endurance sports.

Conflict of Interest: Authors declare no conflict of interest

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