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EFFECTS OF COMBINED PRECONDITIONING STRATEGIES ON ATHLETIC PERFORMANCE: A RANDOMIZED CROSSOVER TRIAL

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Abstract This study investigated the effects of ischemic preconditioning (IPC), post-activation performance enhancement (PAPE), and their combination (IPC+PAPE) on anaerobic performance in trained male athletes. In a randomized crossover design, participants performed a Wingate test following four distinct warm-up protocols. Statistical analysis revealed that only the PAPE protocol significantly improved maximum and relative maximum power compared to the control group ($p < 0.05$). In contrast, IPC alone did not affect substantially any power parameter, and the combined IPC+PAPE protocol demonstrated no synergistic effect over PAPE alone. These findings confirm that PAPE is an effective short-term strategy for enhancing explosive anaerobic performance. From a practical standpoint, this study suggests that while coaches can effectively utilize PAPE protocols to acutely boost power output, combining them with IPC may not provide additional benefits for Wingate performance, thereby questioning their time efficiency in a warm-up setting.

Key words: anaerobic performance, ischemic preconditioning, postactivation potentiation, warm-up

Introduction

Various warm-up strategies are employed prior to training sessions and competitions to enhance athletic performance (Civan et al., 2023; Zarei et al., 2018). In recent years, these strategies, including ischemic preconditioning (IPC) and post-activation performance enhancement (PAPE) protocols, have attracted significant interest from sports scientists (Akgül et al., 2024; Souza et al., 2024).

IPC is typically defined as repeated cycles of temporarily reducing local blood flow, followed by reperfusion, either before (De Groot et al., 2010) or after (Arriel et al., 2018) exercise. Common IPC protocols involve application of pressure within a broad range (e.g., from 10 mmHg above systolic blood pressure to over 300 mmHg) or individualized targeting using the individual's arterial occlusion pressure (Slysz & Burr, 2021). IPC has been extensively researched across various sporting disciplines, exercise modalities, and intensity levels (Marocolo et al., 2018). Over the past 22 years, evidence has demonstrated its its capacity to acutely enhance isometric force

production (approximately 20%), leading to a surge in research investigating these effects. However, persistent heterogeneity in results and protocols remains a significant challenge (O'Brien & Jacobs, 2021 Nevertheless, recent meta-analyses suggest that IPC's influence extends beyond isometric strength to encompass aerobic and anaerobic performance parameters (Chen et al., 2024). Potential mechanisms proposed include hyperemia (a 5-6-fold increase in muscle blood flow) during reperfusion (Libonati et al., 2001), decreased ATP consumption, increased phosphocreatine production, and enhanced oxygen uptake during the reperfusion phase (Andreas et al., 2011). PAPE, in contrast, is defined as an acute enhancement of athletic performance (including maximum strength, power, and speed) following prior loading during warm-up (Kasicki et al., 2024). While some researchers have proposed mechanisms underlying the post-activation potentiation (PAP) effect observed in the literature, the theoretical link to PAPE remains, with the exact mechanisms supporting PAPE not yet fully elucidated. same researchers note that the temporal profile of myosin light chain phosphorylation, a key proposed mechanism for PAPE, rarely overlaps with the temporal profile of strength gains. Furthermore, unlike PAP, alterations in muscle temperature, intracellular water content, and muscle activation could contribute, at least in part, to the observed strength enhancement, potentially explaining the phenomenon termed PAPE (Blazevich & Babault, 2019). Several pre-load strategies are employed to elicit PAPE. Heavy resistance exercises (80% or greater of one repetition maximum (1RM)) are commonly used as pre-load strategies (Sanchez-Sanchez et al., 2018). In this context, a recent systematic review and meta-analysis indicates that resistance exercises applied during warm-up have a more pronounced effect on athletes' jump and sprint performance compared to plyometric or complex exercises (Liu et al., 2024), Previous studies have consistently supported the efficacy of resistance exercises using maximal or near-maximal contractions during warm-up (Prieske et al., 2020; Vargas-Molina et al., 2021).

Studies examining the application of IPC and PAPE within warm-up protocols, and contrasting them with other warm-up methods, exist. However, studies directly comparing these two methods are limited. Furthermore, no studies have been found combining these two approaches within a single warm-up protocol. Given their potential applicability and influence on performance improvements, this study aims to investigate the effects of pre-exercise interventions involving different conditions (IPC, PAPE, and IPC+PAPE) on anaerobic performance.

Material and Methods

Participants

The study involved 16 healthy male volunteers with al least three years of strength training experience. The mean age of the participants was 22.56 ± 2.09 years, mean training experience was 5.88 ± 1.46 years, mean height was 174.56 ± 5.23 cm, mean weight was 70.48 ± 9.15 kg, mean BMI was 23.08 ± 2.35 kg/m ², mean body fat percentage was 16.52 ± 5.48%, mean body muscle mass was 33.2 ± 3.83 kg, mean one repetition maximum (1RM) was 125.47 ± 16.28 kg, and mean 1RM/kg was 1.78 ± 0.13%. Descriptive characteristics of the participants are presented in Table 1. The study adhered to the principles of the Helsinki Declaration and was approved by the Karabük University Faculty of Medicine Non-Interventional Clinical Research Ethics Committee (date: December 26, 2023, no: 2023/1601).

Table 1. Baseline physical characteristics of participants. (n = 16)

Variables	Mean ± SD
Age (years)	22.56 ±2.09
Training experience (years)	5.88 ±1.46
Height (cm)	174.56 ±5.23
Body weight (kg)	70.48 ±9.15
BMI (kg/m ²)	23.08 ±2.35
Body fat percentage (%)	16.52 ±5.48
Body muscle mass (kg)	33.2 ±3.83
1 RM (kg)	125.47 ±16.28
1RM/Body weight (%)	1.78 ±0.13

BMI = body mass index. RM = repetiton maximum. Kg = kilogram. SD = standard deviation.

Measurements

Height and Body Composition Measurements

Participant height was measured using a stadiometer with a precision of 0.01 mm. Body weight and body mass index were determined using an InBody 270 (Biospace, California, USA) device.

Wam-up Protocol

Participants performed 5 minutes of continuous running at a constant speed of 6.5 km/h on a treadmill, followed by 2 minutes of dynamic stretching. Static stretching, jumping, and sprinting were discouraged prior to the warm-up (Sarı et al., 2022).

1 Repetition Maximum Test

The exercise was performed using a Smith Machine (Fitness Center, Hasan Doğan Faculty of Sports Sciences, Karabük University, Turkey). Following the warm-up protocol, participants performed 8–10 repetitions of the back squat (BS) without weight on the machine. Subsequently, they performed 3–5 repetitions with a weight approximating 60–80% of their estimated 1RM. A 2-minute rest period followed, during which they performed 2–3 repetitions at approximately 90–95% of their estimated 1RM. A 4-minute rest period followed. Finally, a 1RM attempt was made, with the 1RM value determined over 4–5 attempts (ACSM, 2018). Throughout the testing, the exercise form adhered to the same protocol as that for the PAPE protocol.

Experimental Procedures

The study was conducted at the Performance Laboratory and Fitness Center of the Hasan Doğan Faculty of Sports Sciences, Karabük University. Participants attended the facility for a total of six days, with all testing sessions separated by intervals of 48 to 72 hours. Participants were instructed to avoid strenuous physical activity in the days leading up to the study and to monitor their carbohydrate intake. On day one, participants received study information, and height, weight, and body fat percentage (determined using the InBody 270 device) were recorded. After collecting the participants' characteristics, a familiarization session was conducted to acclimate participants to the warm-up protocol and subsequent tests. After a 48-hour interval, a standard warm-up protocol was followed,

and the 1RM was determined and recorded. A second 48-hour interval separated the subsequent testing days, during which different conditions (control, IPC, PAPE, IPC+PAPE) were applied at various time points. To avoid any lingering effects of IPC, 72-hour intervals were used between days 3, 4, 5, and 6. To mitigate the impact of time on the results, the study employed a randomized crossover design, with participants equally divided into four groups. Participants were instructed to refrain from eating for 1.5 hours before any intervention. Informed consent was obtained from all participants. Participants were allowed to consume water (500ml) during testing, and verbal encouragement was provided to athletes during the Wingate Test. Figure 1 presents the study design.

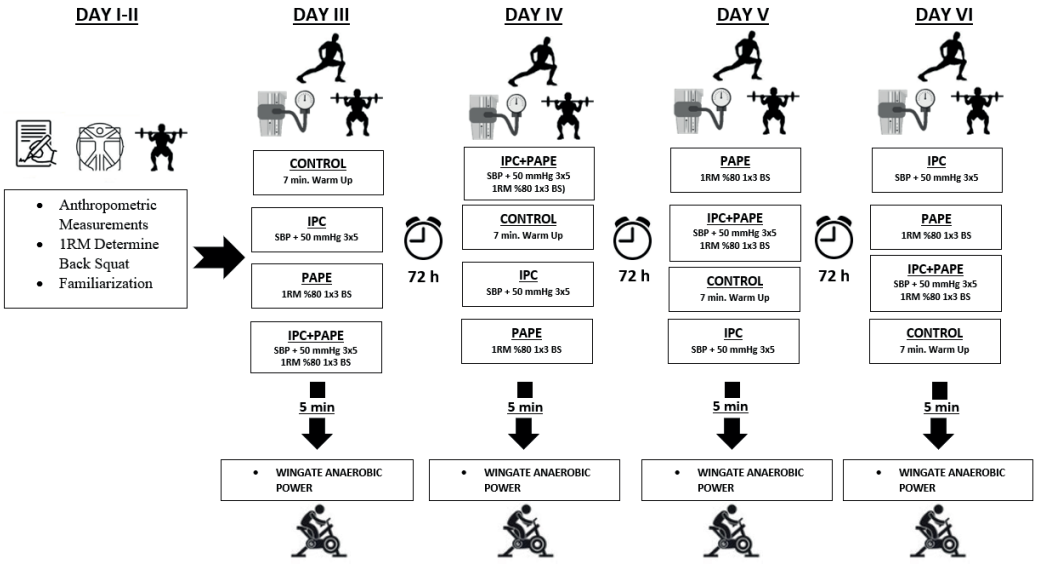

Figure 1. Experimental Procedures

PAPE protocol

Following the warm-up session, a single set of three repetitions of the back squat (BS) exercise was performed using a Smith machine, at 80% of the determined maximum, as is standard practice in other studies (Prieske et al., 2018; Petisco et al., 2019). The exercise was performed with feet shoulder-width apart and in a controlled manner. Participants were instructed to maintain foot contact with the ground and to descend until the knee angle reached 90 degrees. The completion of the squat was indicated by contact between the participant's hamstring and a resistance band placed on the floor, marking the 90-degree knee angle zone (Tseng et al., 2021).

IPC Protocol

Participants performed occlusion and reperfusion phases while seated, with knees at 90 degrees, using a cuff (Reiser, Germany) (Marocolo et al., 2017). All interventions commenced with blood pressure assessment. Occlusion was initiated by applying a pressure 50 mmHg above systolic blood pressure. Participant blood pressure

and applied pressures for each protocol are detailed in Table 2. The intervention began with the right leg, and the cuff was positioned as close to the groin as possible. The procedure lasted 30 minutes, comprising 3 cycles of 5 minutes occlusion followed by 5 minutes of reperfusion. Peripheral pulse monitoring was achieved at the ankle artery region during the occlusion phase (Gürses, 2015).

Table 2. Participants' blood pressure and applied pressure values, according to the implemented protocols (n = 16)

Variables	Mean ±SD
IPC SBP (mmHg)	123.06 ±5.27
IPC DBP (mmHg)	69.78 ±7.16
IPC+PAPE SBP (mmHg)	123.41 ±7.23
IPC+PAPE DBP (mmHg)	73.91 ±9.42
IPC pressure (mmHg)	173.06 ±5.27
IPC+PAPE pressure (mmHg)	173.41 ±7.23

IPC = Ischemic preconditioning. PAPE = Post-activation performance enhancement. SBP = systolic blood pressure. DBP = diastolic blood pressure. SD = standard deviation.

IPC+PAPE Protocol

Following the occlusion and reperfusion cycles of the IPC protocol, participants immediately continued with the warm-up protocol without interruption. The warm-up was then followed by the BS exercise, completing the PAPE protocol.

Wingate Test Protocol

Following all conditions, a 5-minute rest period (Seitz & Haff, 2016) was allowed before the Wingate test (Monark 894 E, Sweden) was administered. A resistance corresponding to 7.5% of the participant's body weight was applied for the 30-second maximal effort. Participants remained seated throughout the test. Power output data were sampled at 10 Hz throughout the test. The highest power value recorded within a 1-second interval was defined as peak power. Average power output was determined as the average power output throughout the 30-second test duration. The lowest power value recorded within a 1-second interval was defined as minimum power. All values were recorded in Watts and also evaluated in W/kg to determine relative power output.

Blood Pressure Measurement

A manual sphygmomanometer was used to determine systolic and diastolic blood pressure of the participants. After a 5-minute rest period in a room-temperature environment, participants' left arms were used for blood pressure measurement. Each measurement was taken twice, with a one-minute interval between readings, and the average value was expressed in mmHg. If the results differed by more than 5 mmHg, a third measurement was taken, and the average of the two closest values was recorded.

Statistical Analysis

Data analysis was performed using IBM SPSS 27 (IBM Corp., Armonk, New York, USA) and Microsoft Excel 2019 (Microsoft Corp., Seattle, WA, USA). A Shapiro-Wilk test was used to confirm normality. Wingate test measures were evaluated using a one-way repeated measures analysis of variance (ANOVA). The sphericity assumption was assessed using Mauchly's test. Where sphericity was violated (Epsilon < 0.75), Greenhouse–Geisser corrections were

applied; where Epsilon > 0.75, Huynh–Feldt corrections were applied. Significance was set at $p < 0.05$ for all analyses. Effect size was evaluated using eta-squared (η^2), categorized as small (≤0.05), medium (0.06–0.13), or large (≥0.14).

Results

This section analyzes the responses of athletes subjected to different warm-up protocols on the Wingate test. Table 3 presents the anaerobic power values for the control group and the various intervention groups.

Table 3. Anaerobic power values for the control, IPC, PAPE, and IPC+PAPE protocols (n = 16)

Variables	Control	IPC	PAPE	IPC+PAPE	F	p	η2
	Mean ±SD						
Maximum Power (W)	779.69 ±141.57	782.88 ±118.12	792.65 ±159.8	783.06 ±159.56	5.56	*0.04**	0.27
Maximum Power (W/kg)	11.17 ±2.14	11.18 ±1.5	11.29 ±1.95	11.19 ±1.98	5.23	*0.05**	0.26
Avarage Power (W)	569.6 ±80.6	566.4 ±67.31	583.12 ±83.45	550.93 ±85.31	2.39	*0.10*	0.14
Avarage Power (W/kg)	8.25 ±0.99	8.23 ±0.69	8.49 ±1.02	7.99 ±1.01	2.54	*0.08*	0.15
Minimum Power (W)	330.26 ±64.46	326.97 ±54.5	321.88 ±75.75	320.35 ±55.14	0.21	*0.82*	0.01
Minimum Power (W/kg)	4.82 ±0.74	4.74 ±0.61	4.68 ±1.11	4.66 ±0.74	0.24	*0.78*	0.02
Power Drop (W)	480.03 ±117.28	449.66 ±106.36	482.36 ±122.96	451.63 ±17.39	2.05	*0.12*	0.12
Power Drop (W/kg)	6.96 ±1.63	6.55 ±1.54	6.98 ±1.66	6.55 ±1.91	1.97	*0.14*	0.12

IPC = Ischemic preconditioning. PAPE = Post-activation performance enhancement. SD = standard deviation. W = Watt. Kg = kilogram. W/kg = relative strength. * = $p < 0.05$.

Analysis of the differences in maximum power (W) and maximum power (W/kg) across conditions revealed that the control protocol exhibited no significant difference compared to the IPC protocol. However, a statistically significant difference was found when comparing the control protocol to the PAPE protocol. No significant difference was observed between the control protocol and the IPC+PAPE protocol. The IPC protocol, when compared to the control, showed no significant difference, but did demonstrate a statistically significant difference compared to the PAPE protocol. No significant difference was found between the IPC protocol and the IPC+PAPE protocol. PAPE demonstrated statistically significant differences when compared to both the control and IPC protocols. Importantly, a statistically significant difference was also observed between the PAPE and IPC+PAPE protocols. The IPC+PAPE protocol did not show a significant difference compared to the control or IPC protocols, but did exhibit a statistically significant difference compared to the PAPE protocol ($p < 0.05$) (Table 4).

Table 4. Pairwise comparisons of maximum power (W) with Bonferroni correction

Variables	Protocol	Mean ±SD	Protocol	Mean ±SD	p
Maximum Power (W)	CON	779.69 ±141.57	IPC	782.88 ±118.12	*1.00*
			PAPE	792.65 ±159.8	*0.05**
			IPC+PAPE	783.06 ±159.56	*1.00*
	IPC	782.88 ±118.12	CON	779.69 ±141.57	*1.00*
			PAPE	792.65 ±159.8	*0.05**
			IPC+PAPE	783.06 ±159.56	*1.00*
	PAPE	792.65 ±159.8	CON	779.69 ±141.57	*0.05**
			IPC	782.88 ±118.12	*0.05**
			IPC+PAPE	783.06 ±159.56	*0.05**
	IPC+PAPE	783.06 ±159.56	CON	779.69 ±141.57	*1.00*
			IPC	782.88 ±118.12	*1.00*
			PAPE	792.65 ±159.8	*0.05**

Con = Control. IPC = Ischemic preconditioning. PAPE = Post-activation performance enhancement. SD = standard deviation. W = Watt. Kg = kilogram. * = $p < 0.05$.

Analysis of relative maximum power (W/kg) revealed no significant difference between the control protocol and the IPC protocol. However, a statistically significant difference was observed when comparing the control protocol to the PAPE protocol. No significant difference was found between the control protocol and the IPC+PAPE protocol. The IPC protocol, when compared to the control protocol, demonstrated no significant difference, and no significant difference was found when compared to the PAPE or IPC+PAPE protocols. The PAPE protocol, on the other hand, showed a statistically significant difference compared to the control protocol, but no significant differences were observed when compared to the IPC or IPC+PAPE protocols. Finally, the IPC+PAPE protocol showed no significant differences when compared to the control or IPC protocols, nor when compared to the PAPE protocol ($p > 0.05$) (Table 5).

Table 5. Pairwise comparisons of relative maximum power (W/kg) with Bonferroni correction

Variables	Protocol	Mean ±SD	Protocol	Mean ±SD	p
Maximum Power (W/kg)	CON	11.17 ±2.14	IPC	11.18 ±1.5	*1.00*
			PAPE	11.29 ±1.95	*0.05**
			IPC+PAPE	11.19 ±1.98	*1.00*
	IPC	11.18 ±1.5	CON	11.17 ±2.14	*1.00*
			PAPE	11.29 ±1.95	*0.06*
			IPC+PAPE	11.19 ±1.98	*1.00*
	PAPE	11.29 ±1.95	CON	11.17 ±2.14	*0.05**
			IPC	11.18 ±1.5	*0.06*
			IPC+PAPE	11.19 ±1.98	*0.06*
	IPC+PAPE	11.19 ±1.98	CON	11.17 ±2.14	*1.00*
			IPC	11.18 ±1.5	*1.00*
			PAPE	11.29 ±1.95	*0.06*

Con = Control. IPC = Ischemic preconditioning. PAPE = Post-activation performance enhancement. SD = standard deviation. W = Watt. Kg = kilogram. * = $p < 0.05$.

Discussion

The most significant finding of this study is that the PAPE protocol demonstrated a statistically significant improvement in maximum power (W) and relative maximum power (W/kg) compared to the control and other protocols. Conversely, no statistically significant differences were observed in the average power, minimum power, or power decline parameters. This finding aligns substantially with the results of similar studies in the existing literature, although variations exist based on the subject pool, protocol duration, and methodologies employed.

These findings regarding the PAPE protocol support the mechanisms proposed by Hamada et al., (Hamada et al., 2000). focusing on increased motor unit activation and myosin light chain phosphorylation as contributing factors to enhanced power output. Tillin et al. highlight the pronounced effect of PAPE, particularly in short-duration, high-intensity activities, linking this effect to increased calcium sensitivity resulting from myosin phosphorylation (Tillin et al., 2012). Similarly, Mitchell and Sale observed improvements in vertical jump performance following a 5RM squat exercise, attributing these improvements to both mechanical and neuromuscular adaptations (Mitchell & Sale, 2011). This corroborates the maximum power enhancement observed in our study using the PAPE protocol. Furthermore, Seitz and Haff., suggest that AIPA is more effective in trained athletes than in untrained individuals, potentially explaining the heightened responsiveness to the PAPE protocol exhibited by the trained participants in this study (Seitz & Haff, 2016).

Relative maximum power (W/kg), representing power normalized to individual body weight, is a critical performance indicator, particularly for athletes. Our study observed an average relative maximum power output of 11.29 ± 1.95 W/kg with the PAPE protocol, demonstrating a significant improvement compared to the control group. This finding aligns with Chiu et al., (2003) observation that PAPE exhibits a more pronounced effect in trained athletes. Existing literature consistently indicates that PAPE is more effective in individuals with a substantial training history, and that body-weight-normalized values often reveal these effects more clearly (Seitz & Haff, 2016). Furthermore, Hodgson et al. (2005), noted a short-term performance-enhancing effect of AIPA on the neuromuscular system, particularly evident in dynamic activities. Our findings suggest that AIPA is an effective method to enhance athletes' anaerobic performance.

Average power (W) and relative average power (W/kg) are crucial indicators of anaerobic performance sustainability. In this study, no statistically significant differences were found in these parameters across the various protocols. However, a moderate effect size ($\eta^2 = 0.14$) was observed between the PAPE and control groups. Existing literature suggests that PAPE is particularly effective in activities requiring explosive power over short durations, but its effect on sustained anaerobic performance is limited (Hodgson et al., 2005). The lack of significant effects on average power in our study aligns with this literature, suggesting a limited impact of PAPE on prolonged exertion requiring sustained power output.

No significant effect of the IPC protocol was observed on maximum power and relative maximum power in our study. However, the literature surrounding IPC's effects on performance remains somewhat controversial, with some studies reporting positive findings and others showing limited or no effect. For example, Bailey et al. (2012) indicated that IPC can improve endurance running performance by reducing lactate accumulation. Yet, the effect of IPC on anaerobic activities appears more limited. Similarly, Crisafulli et al. (2011) reported that IPC can delay muscle fatigue, potentially enhancing performance in short-duration, high-intensity exercise. However, our study did not find a statistically significant effect of IPC on this type of activity. The literature emphasizes that the effectiveness of IPC is contingent on protocol duration, pressure levels, and timing of application (Marocolo et al., 2016). In our study, the

IPC protocol, using a pressure of 173.06 ± 5.27 mmHg, showed more limited results compared to studies employing different pressure levels. While Gürses et al. (2017) observed significant improvements in anaerobic performance in footballers using an IPC protocol, the lack of a similar effect in our study highlights the variable impact of this protocol based on individual differences and exercise type. Furthermore, Incognito et al. (2016) suggested that the variability in responses to IPC (with some participants showing performance improvement, others not) indicates the importance of cautious interpretation due to potential phenotypic differences in responses to this protocol.

The combined application of IPC and PAPE (IPC+PAPE) did not demonstrate the expected synergistic effect in our study. Findings indicate that the IPC+PAPE combination did not enhance maximum power or relative maximum power compared to AIPA alone. This result aligns with Bouffard et al. (2021) work emphasizing the limited influence of IPC on neuromuscular adaptations. While Carvalho and Barroso suggest IPC can improve sustained power performance, they also indicate a lack of substantial evidence supporting the effectiveness of combined protocols with PAPE (Carvalho & Barroso, 2019). Similarly, Griffin et al. (2018) highlighted potential positive effects of IPC on critical power performance but did not definitively demonstrate a further enhancement when combined with PAPE.

The combined application of IPC and PAPE (IPC+PAPE) did not demonstrate the expected synergistic effect in our study, as the findings indicated that this combination did not enhance maximum power beyond that achieved with PAPE alone. Several potential mechanisms could explain this lack of a synergistic benefit. First, a physiological ceiling effect may be at play; the PAPE protocol, involving high-intensity contractions, may have already elevated motor unit recruitment and calcium sensitivity to a near-maximal level, leaving little room for IPC to provide an additional ergogenic effect (Seitz & Haff, 2016). Second, the combination of two distinct physiological stressors—ischemic and mechanical—could have induced greater accumulated fatigue than potentiation. While each protocol is designed to enhance performance, their combined application within a short timeframe might have tipped the balance towards fatigue, thereby masking any potential additive benefits (Incognito et al., 2016).

Furthermore, the timing and duration of the protocols are critical. The optimal potentiation windows for IPC and PAPE may not align perfectly. It is plausible that the 5-minute rest period implemented in our study was not sufficient or ideally timed to capitalize on the peak effects of both interventions simultaneously (Carvalho & Barroso, 2019). Finally, the distinct underlying mechanisms of IPC (e.g., enhanced blood flow, metabolic efficiency) and PAPE (e.g., neural activation, myosin light chain phosphorylation) may interact in a complex or even antagonistic manner, where the effects of one protocol could potentially neutralize or interfere with the other. Future research should therefore investigate the combined effect of IPC and PAPE with varying recovery periods, protocol intensities, and subject characteristics to better understand how to optimize these strategies for anaerobic performance

A key limitation of this study is the relatively small sample size (n = 16), which may have limited the statistical power to detect small to moderate effects and could increase the risk of a Type II error.

In conclusion, this study demonstrates that the PAPE protocol is effective in enhancing short-term anaerobic power performance. No significant effect of the IPC protocol was observed on maximum or average power parameters. The combination of IPC and PAPE did not yield the expected synergistic effect, suggesting the need for optimization of protocol durations and intensities. Future research should investigate the combined effect of IPC and PAPE with varying recovery periods, protocol intensities, and subjects with different training levels. Such studies could provide a clearer understanding of the impact of both IPC and PAPE on anaerobic performance.

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