European Journal of Applied Physiology (2019) 119:1431–1437
https://doi.org/10.1007/s00421-019-04133-6

ORIGINAL ARTICLE

Impact of 8 weeks of repeated ischemic preconditioning on running performance

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Received: 13 November 2018 / Accepted: 28 March 2019 / Published online: 5 April 2019

Abstract

Purpose To examine if repeated exposure to IPC treatment prior to training sessions improves oxygen uptake and 1-km running performance in highly trained middle-distance runners.

Methods Fourteen highly trained endurance runners (11 male/3 female, 19 ± 2 years, 64 ± 5 ml kg^{-1} min^{-1}) completed a baseline maximal oxygen consumption ($\dot{V}O_{2max}$) test and 1-km running performance test before random assignment to an IPC or control group. Both groups were prescribed identical endurance training over an 8-week varsity season; however, the IPC group performed an IPC protocol (5 min ischemia, repeated 3 times, each separated by 5 min reperfusion) before every training session. After 8 weeks of training, participants completed a follow-up $\dot{V}O_{2max}$ test and 1-km time trial.

Results $\dot{V}O_{2max}$ did not increase from baseline in either group following the 8-week training bout ($P = 0.2$), and neither group varied more than the other ($\Delta\dot{V}O_{2max}$ = IPC 0.6 ± 2 ml kg^{-1} min^{-1}; control 1.5 ± 2 ml kg^{-1} min^{-1}, $P = 0.6$) or beyond typical measurement error. The IPC decreased 1-km time trial time by 0.4% (0.5 ± 2 s), while the control group decreased by 1% (1.5 ± 3 s), but neither change was significant compared to baseline ($P = 0.2$). There was also no difference in time trial improvement between IPC and control ($P = 0.6$). However, there was a trend towards IPC significantly improving running economy at low intensity ($P = 0.057$).

Conclusion Our data suggest that over a normal 8-week season in a population of highly trained middle-distance runners there is no benefit of undergoing chronic, repeated IPC treatments before training for augmenting maximal aerobic power or 1-km performance time.

Keywords Exercise · Running · IPC · Occlusion · Hypoxia

Abbreviations

IPC	Ischemic preconditioning
$\dot{V}O_2$	Oxygen consumption (ml kg^{-1} min^{-1})
VE	Ventilation (L/min)
RER	Respiratory exchange ratio
LOP	Least effective occlusive pressure (mmHg)

Introduction

Competitive athletes seek to optimize a training framework that stimulates progressive adaptation and performance. Due to diminishing returns on traditional training, athletes often look for additional preparatory strategies or techniques in an attempt to gain a competitive advantage; some of which are used to augment training effects and recovery over time, while others are applied just prior to competition to provide a more immediate advantage. A recent strategy for acutely improving performance is ischemic preconditioning (IPC) (De Groot et al. 2010; Jean-St-Michel et al. 2011). IPC is characterized by the application of brief periods of circulatory occlusion and reperfusion of a limb in the minutes to hours preceding exercise (Murry et al. 1986). As a method that is easily administered, non-invasive, and inexpensive, it represents an attractive ergogenic aid for athletes to augment performance.

Communicated by Anni Vanhatalo.

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The most consistently observed athletic benefit of acute IPC treatment is an improvement in time-trial performance for events lasting > 75 s (Incognito et al. 2016). While IPC is more likely to be ergogenic during endurance exercise, the mechanisms that underlie the ergogenic effects of IPC are unclear. Recently, Griffin et al. (2018) observed an improved critical power following IPC and suggested that IPC has the potential to improve endurance performance by enhancing capacity in the severe intensity exercise domain. Acute application of IPC improves muscular endurance at severe-intensity, as evidenced by improved skeletal muscle oxygenation (Kido et al. 2015; Tanaka et al. 2016); while short-term (7–10 days) (Jeffries et al. 2018) and long-term (8 weeks) (Jones et al. 2015) exposure to repeated IPC sustains this enhanced skeletal muscle oxidative capacity beyond the reported acute late phase of protection following IPC (72 h) (Loukogeorgakis et al. 2005). In addition, it is known that IPC can improve recovery from muscle damaging exercise (Page et al. 2017; Franz et al. 2018), and it is therefore possible that IPC would allow athletes to maximize outputs during each training session. As such, repeated exposure to IPC should permit for an enhanced high-intensity endurance performance over time. However, to date, studies investigating the effectiveness of repeated IPC for improving performance remain limited and conflicting (Banks et al. 2016; Lindsay et al. 2017).

High-performance research completed within an athlete's complex training environment is of practical value for both coach and athlete (Peacock et al. 2019). Evidence suggests that IPC may be efficacious as an ergogenic aid to gain a competitive edge, however, current literature lacks a proper evaluation of IPC as a tool that can be practically applied over the course of an athlete's training program. Thus, the purpose of this study was to determine the impact of consistently, and repeatedly undergoing treatment of IPC within an athlete's training block for improving high-intensity endurance performance over time. Specifically, we aimed to investigate the changes in 1-km time trial running performance and maximal oxygen consumption, in highly trained middle-distance runners who employed IPC treatment before training sessions for 8 weeks. It was hypothesized that athletes who underwent IPC treatment would have a greater maximal oxygen consumption and an improved 1-km time trial performance after 8 weeks of training compared with similar athletes who did not undergo IPC treatment.

Methods

Participants

Sixteen highly trained middle-distance runners were recruited from the most successful Varsity Track and Field team in the country. For all participants, 1 km was a competitive distance with which they were familiar. Fourteen participants completed the study, and two participants withdrew due to injuries unrelated to the study protocol. At the time of the study, all runners were involved in regular training (10–15 h/week). Their personal best times for the 1000 m are shown in Table 1. All participants had a high maximum oxygen consumption ($\dot{V}O_{2max}$, 65 ± 6 ml kg^{-1} min^{-1}). The study was approved by the University ethics committee and conformed to the Declaration of Helsinki, with all participants providing written informed consent prior to enrollment.

Research design

Participants reported to the laboratory to complete a baseline $\dot{V}O_{2max}$ test. At least 48 h later, but within 1 week, all participants then performed a 1-km running time trial on a 200 m indoor polytran track surface. Stratified randomization by sex and coin flip was used to assign athletes to either the IPC treatment ($n = 7$, 6 male/1 female, 18 ± 1 years, 67 ± 3 kg, 178 ± 3 cm) or control ($n = 7$, 5 male/2 female, 19 ± 2 years, 67 ± 10 kg, 181 ± 12 cm) group. Both groups were prescribed identical training over the next 8 weeks; however, the IPC group performed IPC treatments before training. The groups were initially matched for sex, but due to dropout, 1 female in the IPC group and 1 male in the control group did not complete the study. After 8 weeks of training, each participant underwent a follow-up time trial and $\dot{V}O_{2max}$ test at least 48 h, but at most 1 week following the last IPC intervention. Participants refrained from alcohol, caffeine and strenuous exercise 24 h before all baseline and follow-up performance testing.

Experimental measurements

A continuous incremental test on a motorized treadmill (Pulsar 4.0; h/p/cosmos, Willich, Germany) was used to assess maximal oxygen consumption ($\dot{V}O_{2max}$). The test commenced after a 5-min self-paced warm-up ranging between

Table 1 Personal best running times for the 1000 m run of the 15 athletes in the study

Athlete experimental	Personal best time (s)	Athlete control	Personal best time (s)
1	150.37	1	188.22
2	150.07	2	148.66
3	190.00	3	154.91
4	151.25	4	186.43
5	156.11	5	159.70
6	155.03	6	181.11
7	161.14	7	145.09

4 and 6 mph. Continuous 2-min stages were performed (0.5 mph and 1% grade increment per stage) starting at 6 mph for females and 9 mph for males. During the test, breath by-breath expired gases were monitored using open circuit spirometry (COSMED Quark CPET, Rome, Italy) and $\dot{V}O_2$ (ml kg^{-1} min^{-1}), ventilation (VE, L/min), and RER were averaged over the last 30 s of breath-by-breath data of each stage. This $\dot{V}O_2$ average at each stage was used to investigate the oxygen cost at each running velocity over this time (running economy). Achievement of $\dot{V}O_{2max}$ was considered as the attainment of a plateau in oxygen uptake (< 150 ml min^{-1} increase) despite increasing workload, a rating of perceived exertion ≥ 19–20, and an RER ≥ 1.15. The maximal values were represented as the highest value to occur after the data was smoothed using a 30-s rolling average.

Before each 1-km time trial, participants performed a standard 15 min warm-up period that included low-intensity running, several acceleration runs and stretching, as per individual race preparatory strategy. Time trials were performed individually, with athletes wearing running spikes typically used during competition. Participants were advised to use a normal race strategy and were verbally encouraged by the researcher and their coach to perform to maximum effort during the trial. Performance times were recorded every 200 m by the same researcher using a hand-held chronometer (Lowell YT0401, China), and athletes were informed of their single lap times at 200 m and 400 m but were blinded to their last three lap times. This was to ensure that athletes ran by feel, as opposed to locking in on a predetermined pace, which may have prevented potential improvement. Baseline and follow-up time trials were scheduled around the same time of day between 15:00 h and 18:00 h.

Training intervention

During the time of the study, athletes were in a general preparation training phase and did not participate in any competitive event. All participants underwent the same training involving three organized high-intensity group sessions and three additional lower-intensity individual running sessions per week, for 8 weeks. Each high-intensity group session involved a total of 40 min at an easy intensity (~4.7 min/km), 10 min at a tempo intensity (~3.3 min/km), and 3 min at 1 km race pace (~2.5 min/km). Each week, the three high-intensity sessions totalled ~160 min and ~40 km of running. The three lower-intensity individual running sessions per week included two sessions of 45 min and one session of 70 min at a low-intensity pace (~4.7 min/km) that totalled ~160 min and ~35 km of running. Over the course of the 8-week study, training was periodized by gradually exposing athletes to their specific race pace (1000 m) in preparation for the upcoming indoor season set to begin soon after the conclusion of the 8-week study. This training was designed and implemented by the coach. Participants in the IPC group arrived 40 min before the start of all high-intensity group sessions to undergo an IPC treatment. Compliance with training session participation over the 8 weeks was 92–100%.

Ischemic preconditioning was performed in a sitting position using unilateral arterial occlusion of a leg. Occlusion was accomplished using a PTSi automated tourniquet system (Defli Medical Innovations Inc. Vancouver, Canada). Unilateral IPC has been proposed to induce a systemic preconditioning effect (Kharbanda et al. 2002), and past research using a unilateral IPC model has shown to improve performance in whole body exercise such as 100 m swim time (Jean-St-Michel et al. 2011) and 1 km rowing time (Kjeld et al. 2014). The occlusion cuffs were positioned proximally around the right thigh and inflated above systolic pressure, ensuring complete arterial occlusion. Specifically, we employed the lowest effective occlusion pressure (LOP), which can be detected by the Delfi system for each participant by utilizing a probe to detect the pressure required to cause the distal pulse to disappear (Masri et al. 2016). LOP was determined in duplicate and the average of these two values was used to set the pressure for circulatory occlusion. Circulatory occlusion lasted 5 min and was performed three times, each separated by 5 min of reperfusion. No participant complained of undue pain or discomfort during the periods of leg circulatory occlusion.

Statistical analysis

The primary outcomes were performance time to complete a 1-km time trial and maximal oxygen consumption during a continuous incremental running test to exhaustion. These variables were analyzed using a 2 × 2 repeated measures ANOVA (two level: IPC and Control) and time (two levels: pre- and post-8-week intervention). Similarly, a two-factor general linear model was used to analyze the submaximal variables of $\dot{V}O_2$, VE, and RER during the first three stages of the continuous incremental running test to exhaustion. Significant effects were examined using the least significant difference method for pairwise multiple comparisons. For all statistical tests, a two-tailed comparison was used. Data are reported as mean ± SD unless stated otherwise, and statistical significance was set at $P \leq 0.05$. All statistical analyses were performed using SPSS 25.0 software (SPSS, Chicago, IL).

Results

1-km time trial

As a whole, the athletes appeared to be marginally faster by 0.7% (− 1.1 ± 0.7 s, 95% CI [− 2.5, 0.2] Cohen's $d = 0.34$)

following 8 weeks of training, but this change in performance on the 1-km time trial did not reach significance as a main effect ($F[1,6] = 1.50$, $P = 0.2$). There was also no significant difference in the magnitude of improvement on the time trial performance between IPC (0.4%, -0.5 ± 2 s, 95% CI [−2.5, 1.4], Cohen's $d = 0.2$) and control (1%, -1.5 ± 3 s, 95% CI [−3.7, 0.23], Cohen's $d = 0.5$) groups ($F[1,12] = 0.65$, $P = 0.4$, Fig. 1).

Maximal aerobic performance

There was no detectable increase in $\dot{V}O_{2max}$ in either group following the 8-week training block ($F[1,12] = 1.87$, $P = 0.2$, Cohen's $d = 0.4$), and neither the IPC group ($\Delta\dot{V}O_{2max} = 0.6 \pm 2$ ml kg^{-1} min^{-1}, 95% CI [−0.7, 1.7], Cohen's $d = 0.4$) or Control group (1.5 ± 2 ml kg^{-1} min^{-1}, 95% CI [0.24, 2.7], Cohen's $d = 0.6$) increased or decreased more than the other ($F[1,12] = 0.463$, $P = 0.6$, Fig. 2). Table 2 shows there were no significant changes across time and between groups in submaximal $\dot{V}O_2$, VE, and RER throughout the continuous incremental test. However, there was a trend found toward a significant decrease ($F[1,6] = 4.74$, $P = 0.057$; Cohen's $d = 0.55$) in $\dot{V}O_2$ at the lowest-intensity submaximal exercise stage.

Discussion

This exploratory trial examined the impact of undergoing consistent, repeated use of IPC before training for improving maximal oxygen consumption and 1 km running performance in highly trained middle-distance runners. The main finding of this study was that 8 weeks of IPC treatment before three high-intensity training sessions per week did not improve maximal oxygen consumption nor 1-km time trial performance more effectively than a control group that did not undergo IPC treatment. Therefore, our data suggest that over the course of a typical 8-week season there is

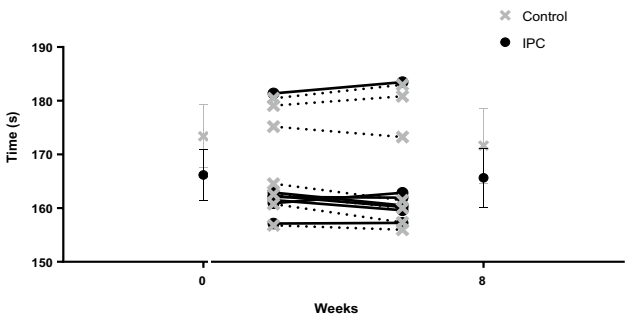

Fig. 1 Individual and mean (SD) 1-km time trial performance before and after 8 weeks of IPC treatment in young highly trained middle-distance runners

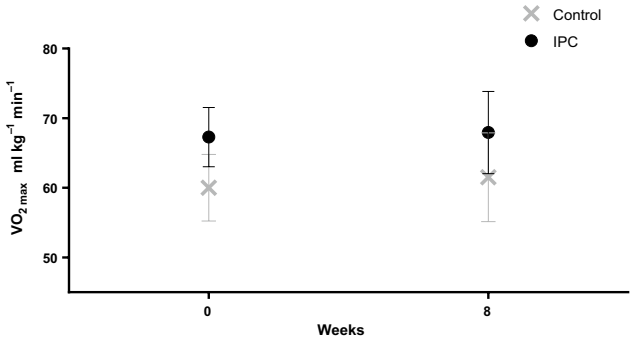

Fig. 2 Individual and mean (SD) $\dot{V}O_{2max}$ performance before and after 8 weeks of IPC treatment before training three times per week in young highly trained middle-distance runners. *Denotes a significant main effect of group ($P = 0.03$)

no apparent benefit of undergoing repeated IPC treatment before training for improving maximal oxygen consumption or running performance over 1 km in a population of highly trained middle-distance runners.

Maximal aerobic performance

While the current data demonstrate repeated IPC to be ineffective for increasing $\dot{V}O_{2max}$ after 8 weeks, previous research has supported the notion of a sustained aerobic adaptation as a result of using IPC. Short-term (7–9 consecutive days) IPC administration has shown to increase skeletal muscle oxidative capacity (Jeffries et al. 2018), enhanced microvascular oxygenated blood flow (Jeffries et al. 2018), and improved vascular conductance (Jones et al. 2014). These adaptations have further been shown to be maintained over the long term (8 weeks) when IPC is applied consistently (Jones et al. 2015). Despite these tissue-level aerobic adaptations from repeated IPC, data supporting a translation to improved whole-body $\dot{V}O_{2max}$ remains conflicted. No change in $\dot{V}O_{2max}$ was observed after 9 consecutive days of IPC (Banks et al. 2016) but Lindsay et al. (2017) observed a very large 9.5% improvement in $\dot{V}O_{2max}$ after 7 consecutive days of IPC, and 12.8% after 7 additional days of no IPC. These improvements in $\dot{V}O_{2max}$ are substantially greater than changes in $\dot{V}O_{2max}$ after a singular bout of IPC (3%) as previously reported by De Groot et al. (2010). Our data suggest that long-term exposure to repeated IPC in well-trained runners either does not cause, or does not maintain, these previously reported effects of short-term repeated IPC on $\dot{V}O_{2max}$. Discrepancies in the populations used between studies should be recognized as the current study used well-trained athletes, while Lindsay et al. (2017) recruited recreationally active participants. It is known that when untrained individuals initiate a training program $\dot{V}O_{2max}$ improves rapidly, but as an individual

Table 2 Oxygen consumption ($\dot{V}O_2$), ventilation (VE) and respiratory exchange ratio (RER) collected during the first three stages of an incremental exercise test before and after 8 weeks of training with or without regular IPC treatment

	Stage 1		*P* value	Stage 2		*P* value	Stage 3		*P* value
	Pre	Post		Pre	Post		Pre	Post	
$\dot{V}O_2$			Time: 0.1			Time: 0.7			Time: 0.6
IPC	47.1 ± 2	44.4 ± 3	Group: 0.09	50.7 ± 3	49.0 ± 3	Group: 0.7	56.2 ± 3	55.5 ± 2	Group: 0.2
Control	42.1 ± 4	42.0 ± 4	Time × group: 0.06	48.3 ± 4	48.8 ± 4	Time × group: 0.4	54.6 ± 5	54.2 ± 4	Time × group: 0.7
VE			Time: 0.9			Time: 0.7			Time: 0.4
IPC	88.6 ± 8	86.1 ± 9	Group: 0.1	103 ± 5	99 ± 4	Group: 0.8	122 ± 9	115 ± 8	Group: 0.6
Control	83.3 ± 16	80.4 ± 13	Time × group: 0.8	94 ± 17	96 ± 16	Time × group: 0.2	120 ± 18	125 ± 15	Time × group: 0.1
RER			Time: 0.6			Time: 0.7			Time: 0.5
IPC	0.88 ± 0.1	0.86 ± 0.1	Group: 0.3	0.88 ± 0.1	0.86 ± 0.1	Group: 0.1	0.92 ± 0.1	0.89 ± 0.1	Group: 0.02
Control	0.87 ± 0.1	0.86 ± 0.1	Time × group: 0.9	0.87 ± 0.1	0.86 ± 0.1	Time × group: 0.3	0.93 ± 0.1	0.90 ± 0.1	Time × group: 0.8

becomes increasingly well-trained, the returns in $\dot{V}O_{2max}$ diminish as genetic limits are approached (Wenger and Bell 1986). In addition, the current study did not apply IPC on consecutive days as did Lindsay et al. (2017), but rather used three non-consecutive times per week. The optimal methodology (frequency, intensity, and duration) for implementing repeated IPC is unknown, and differences between previous studies and the current study could be explained by different methodology of application. The determinants of $\dot{V}O_{2max}$ are complex, but it is generally accepted that exercise in which a large muscle mass is recruited stresses both the central and peripheral limitations of oxygen delivery and uptake (Poole and Richardson 1998). Jones et al. (2014) observed an improved vascular conductance after 7 consecutive days of repeated IPC, and after 8 weeks of 3 non-consecutive days per week, suggesting daily IPC episodes may not be necessary for this effect. If an IPC-mediated improvement in vascular conductance is the mechanism leading to changes in $\dot{V}O_{2max}$, it is unknown why the current study did not observe a such a change. Interestingly, 4 weeks of applying blood flow restriction after sprint interval training has recently been shown to increase $\dot{V}O_{2max}$ (Taylor et al. 2016; Mitchell et al. 2018), suggesting an augmented metabolic stress may be important in long-term aerobic adaptation. Mitchell et al. (2018), did not observe any peripheral adaptations following 4 weeks of repeated IPC after sprint training and suggested that the increase in $\dot{V}O_{2max}$ is perhaps more likely attributed to central adaptations, i.e., increase cardiac output. It is possible that frequency and/or intensity of the IPC stimulus needs to enough to elicit central adaptations and increases in $\dot{V}O_{2max}$.

1-km time trial

Previous studies have investigated running performance after a singular bout of IPC, reporting an increase in 5-km performance on a laboratory treadmill, but not on an athletic track (Bailey et al. 2012; Tocco et al. 2015). Existing literature investigating the effects of repeated IPC on athletic performance has demonstrated that 4 weeks of applying IPC after sprint interval training has no effect on 15-km running performance (Taylor et al. 2016) or cycling critical power (Mitchell et al. 2018). In agreement, our findings demonstrate no change in running performance, using a 1-km time trial, following 8 weeks of repeated IPC.

Previous research has shown that during events as a short as 2 min, exercise intensity will be above 90% of $\dot{V}O_{2max}$ and this intensity may be even higher for longer middle-distance events (Spencer and Gastin 2001). Since the average time for the 1-km time trial in the current study was 169 ± 14 s, athletes were very likely close to $\dot{V}O_{2max}$ throughout the test. As we observed no change in $\dot{V}O_{2max}$, it is perhaps not surprising that there was no change in 1-km time trial performance. Finally, it is worth recognizing that treatment-based differences may have occurred in the IPC group if training were done by individual feel/effort and not as a training group, as the IPC group may have opted to train differently (i.e. harder/longer) if IPC allowed for a greater output of each session.

During submaximal exercise there was a trend toward a decrease in $\dot{V}O_2$ at the lowest-intensity stage of the graded exercise test in the IPC group. A single bout of IPC has been shown previously to have no effect on submaximal $\dot{V}O_2$ (Clevidence et al. 2012), yet Jefferies et al. (Jeffries et al. 2018) reported a decrease in resting muscle metabolism and improved efficiency when performing submaximal (40% 1 RM) plantar flexion exercise in young, active males after 7 consecutive days of IPC. The effect of repeated IPC on running economy has not been previously investigated. An increased running economy could facilitate improved running performance, as it is known that in highly trained distance runners with similarly high $\dot{V}O_{2max}$, running economy is a better predictor of performance than $\dot{V}O_{2max}$ (Morgan

et al. 1989). As previously mentioned, athletes in the current study were most likely at their $\dot{V}O_{2max}$ throughout most of the 1-km performance trial, thus any improvement in submaximal running economy would not be reflected in performance. However, these improvements in low-intensity running economy may benefit longer-distance endurance athletes whose typical race pace is further from $\dot{V}O_{2max}$. Interestingly, running economy was improved at an intensity of 6 and 9 mph for females and males, respectively; a pace that is much lower than typical race pace for middle distance events. At present, changes in submaximal economy after chronic repeated use in training remains speculative and warrants further investigation.

It must be recognized that owing to a limited number of potential participants and small change in performance this investigation had a low statistical power, which inflates the possibility of type II error. However, even in the presence of a type II error, the observed effect was not a change that was meaningful in the context of highly trained middle-distance runners. Repeated IPC treatment resulted in a 0.4% performance improvement after 8 weeks. In all performance related interventions, it is important to consider the magnitude of change at which point an alteration is performance is practically meaningful. It has been suggested that, for an athlete, a performance enhancement will only alter the chance of winning when it is greater than the typical variation between trials. Malcata and Hopkins (2014) reported a 1% typical variation in highly trained runners for distances < 3 km. As such, a 0.4% improvement from 8 weeks of repeated IPC treatment does not have a practically meaningful benefit to 1-km time trial performance in highly trained distance runners. Therefore, even with a higher probability of a type II error, it does not weaken our conclusion of repeated IPC being ineffective for improving 1-km time trial performance after 8 weeks.

Limitations

As with any study, there are a number of limitations to this work that must be recognized. We acknowledge the limitation of the unilateral IPC model, as it could be argued that bilateral IPC may offer a stronger stimulus and be a possible reason for the current study's non-significant finding. The majority of literature suggests no clear relationship between the effects of IPC on performance and amount muscle mass subjected to ischemia (Incognito et al. 2016), as time trial performance has been improved by applying IPC to the arm (Jean-St-Michel et al. 2011; Kjeld et al. 2014) or leg (Crisafulli et al. 2011; Bailey et al. 2012; Barbosa et al. 2015). Additionally, the cytoprotective effects of IPC have been shown to be similar when occlusion was completed three times in the arms and legs (Loukogeorgakis et al. 2005), and the number and duration of cycles rather than the tissue mass exposed to IPC determines the efficacy of protection (Johnsen et al. 2016). However, recent literature specifically examining IPC dosing suggests that bi-lateral occlusion, but not a greater number of IPC cycles, may provide benefit (Cocking et al. 2018). It is noted, however, that this work was performed in cyclists, not runners and the transfer across sports remains unclear.

Comprehensive individual athlete monitoring was not completed by the research team above and beyond the normal athlete–coach interactions and, thus, details on changes in external factors such as nutrition, sleep, or mood states, etc., over the 8 weeks are not known. While this was a necessity for the ecological validity and feasibility of this study it is important to note that the observed non-effect of repeated IPC treatment could have been caused by an uncontrolled variable. Particularly, athletes did not restrict caffeine throughout the 8 weeks due to the impracticality of its exclusion during athletic training. As caffeine has been shown to abolish the cytoprotective effects of IPC (Riksen et al. 2006), it is possible that the IPC effect could have been blunted throughout training. Finally, the inclusion of a sham control for the non-experimental group was omitted, due to limited number of available athletes. As such, it is possible that a placebo effect could have occurred, if participants believed the treatment would help. However, the absence of an IPC effect indicated a lack of placebo effect.

Conclusion

In a group of highly trained middle-distance endurance runners, 8 weeks of consistent, repeated exposure to IPC prior to training did not improve $\dot{V}O_{2max}$ or running performance over 1 km. These findings suggest that the application of IPC as an ergogenic strategy to enhance the training effect and improve high-intensity running performance over a relatively short distance may not be useful in a typical team setting. However, whether this technique could enhance the training effect over time to be ergogenically useful for submaximal running economy or another outcome remains unknown.

Acknowledgements This work was supported by the Natural Sciences and Engineering Research Council of Canada under Grant 03974; Mitacs under Grant IT05783; and the Canada Foundation for Innovation under Grant 460597.

Author contributions JTS and JFB conceived and designed research. JTS conducted experiments, analyzed data, and wrote the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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