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Ischemic preconditioning increases muscle perfusion, oxygen uptake and force in strength-trained athletes

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Abstract

Background: Muscle ischemia and reperfusion induced by ischemic preconditioning (IPC) can improve performance in various activities. However, underlying mechanisms are still poorly understood. **Purpose:** To examine the effects of IPC on muscle haemodynamics and O₂ uptake during repeated maximal contractions. **Methods:** In a cross-over, randomized, single-blind study, ten strength-trained men performed five sets of 5 maximum voluntary knee extensions of the right leg on an isokinetic dynamometer, preceded by either IPC of the right lower limb (3x5-minutes compression/5-minutes reperfusion cycles at 200 mmHg) or SHAM (20 mmHg). Changes in deoxy-haemoglobin ([HHb]), expressed in percentage of arterial occlusion, and total haemoglobin ([THb]) concentrations of the vastus lateralis muscle were continuously monitored by near-infrared spectroscopy. Differences between IPC and SHAM were analyzed using Cohen's effect sizes (ES) ± 90% confidence limits, and magnitude-based inferences. **Results:** Compared to SHAM, IPC likely increased muscle blood volume at rest (↑[THb], 46.5%, ES 0.56, 90% confidence limits for ES -0.21;1.32). During exercise, peak force was almost certainly higher (11.8%, ES 0.37, 0.27;0.47), average force was very likely higher (12.6%, ES 0.47, 0.29;0.66), and average muscle O₂ uptake was possibly increased (15.8%, ES 0.36, -0.07;0.79) after IPC. In the recovery periods between contractions, IPC also increased blood volume after set one (23.6%, ES 0.30, -0.05;0.65) and five (25.1%, ES 0.32, 0.09;0.55). **Conclusion:** Three cycles of IPC immediately increased muscle perfusion and O₂ uptake, conducive to higher repeated force capacity in strength-trained athletes. This manoeuvre therefore appears relevant to enhance exercise training stimulus.

Key words: blood flow restriction, athletes, oxygenation, performance, recovery

Draft

Introduction

During maximal physical exercise, the requirements for oxygen (O_2) are dramatically increased, and several conditioning strategies have been examined to increase and maintain O_2 supply to, and uptake by, active skeletal muscles. Repeated episodes of muscle ischemia followed by reperfusion, known as ischemic preconditioning (IPC), may render different tissues within the body, including skeletal muscle, more resistant to subsequent ischemic/hypoxic insults (Tapuria et al. 2008; Berger et al. 2015). The IPC-induced acute molecular and vascular adaptations may promote local vasodilation, enhance blood flow, and ultimately improve O_2 delivery (Tapuria et al. 2008; Beaven et al. 2012). Thus, IPC has been reported to improve maximal performance in various exercise modes when the oxidative system is fully taxed (de Groot et al. 2010; Bailey et al. 2012b; Kjeld et al. 2014). Surprisingly however, the direct investigation of the impact of IPC on muscle oxidative response (i.e., O_2 extraction) during maximal exercise is very limited. Near-infrared spectroscopy (NIRS) allows examining the activation of the peripheral determinants of O_2 uptake, and would provide the rationale for prescribing and refining such a conditioning method.

To date, a study using NIRS reported a longer time-to-task failure during handgrip exercise at 45% maximal voluntary contraction, associated with a greater tissue deoxygenation after IPC (Barbosa et al. 2015). As acknowledged by the authors, however, the greater deoxygenation in IPC could merely be due to the longer time-to-task failure in IPC, and therefore, does not robustly demonstrate the impact of IPC on O_2 extraction. In another NIRS study, a higher muscle tissue oxygenation was observed

during repeated 6-s sprints after IPC (Patterson et al. 2015). Higher tissue saturation indicates a greater O₂ delivery to the area of investigation. However, the tissue saturation index represents the balance between O₂ delivery and uptake, and does not distinguish between the two. Further, the results were limited to the sprint repetitions and no recovery data were presented.

Interestingly, by promoting muscle blood flow (Enko et al. 2011; Berger et al. 2015), and potentially muscle re-oxygenation, IPC could enhance recovery processes between repeated maximal efforts, which are limited by O₂ delivery (Balsom et al. 1994; Billaut and Buchheit 2013). Data during exercise that impedes blood flow (e.g., isometric or slow, dynamic contractions) are inexistent, although it is intuitive that IPC could prove more beneficial in such metabolic conditions than during free-flow, dynamic exercise. Intramuscular pressure is positively correlated with contraction intensity, and it is accepted that occlusion of muscle blood flow and perfusion occurs at 50-60% maximal voluntary contraction (Saltin et al. 1998; Wigmore et al. 2004). Since IPC impacts vasodilation, the interplay of repeated muscle actions that impede blood flow and oxygenation, with recovery periods between contractions that allow for re-oxygenation, may permit a better understanding of the impact of this manoeuvre on muscle oxidative response. Isolated contractions are also a good alternative to avoid confounding effects that inspiratory muscle fatigue can have on limb-blood flow and O₂ uptake (Christian et al. 2014). Therefore, the current study determined whether IPC improves muscle haemodynamics and O₂ extraction during repeated maximal efforts with an incomplete

recovery period. We specifically used low-speed, isokinetic contractions to impede muscle blood flow and to provide new data on the physiological impact of IPC.

Materials and methods

Participants

Ten strength-trained men (power and weight lifters and taekwondo athletes, 3-5 weight training sessions per week; age 25 ± 4 y; height 1.77 ± 0.06 m; weight 85.8 ± 13.9 kg) volunteered to take part in this study. All participants were non-smokers, free of health problems, did not use any medication, and were asked to avoid vigorous exercise, alcohol and caffeine 24 h before the tests. They all provided written informed consent after being informed of experimental procedures, associated risks and potential benefits. The study was approved by the local institutional ethics committee, and adhered to the principles established in the Declaration of Helsinki.

Experimental design

Participants visited the laboratory for one familiarisation and two experimental trials. Resting heart rate and blood pressure (inclusion criteria $<140/100$ mmHg) were taken prior to every trial. During the first visit, height, weight and thigh circumference were measured. Thigh circumference (62.3 ± 5.1 cm) was measured by the same experimenter, 1 cm under the gluteal line. Participants then completed a familiarisation session with the experimental set-up, comprising of one compression of three minutes at a pressure of 200 mmHg, and a standardised warm-up consisting in 5 minutes cycling on a Monark ergometer (Ergomedic 828 E) at 100 W. Warm-up then included 3 to 5 right-leg

extensions on an isokinetic dynamometer (Kin-Com 500H, Chattecx Corp., Hixson, TN) at 20°/second, with effort perception progressing from 3 to 9 out of a scale of 10. After 2 minutes of rest seating on the dynamometer, participants completed three full sets of the exercise protocol described below.

Following familiarisation, participants were randomized in a single-blind, cross-over design to IPC or SHAM. In both conditions, participants were seated comfortably on a bed with both legs outstretched, and a non-elastic nylon blood pressure cuff (WelchAllyn, Skaneateles Falls, NY, USA, width: 21 cm) was positioned around the right upper thigh, under the gluteal line. In IPC, the cuff was rapidly inflated to 200 mmHg for five minutes, and this was repeated three times with each compression episode separated by 5 minutes of reperfusion in the same position. A plateau in the deoxy-haemoglobin concentration curve was observed in every subject, and taken as a sign of occlusion. In SHAM, the cuff was inflated to 20 mmHg. To minimize any placebo effect, participants were told that the study purpose was to compare the impact of two different cuff pressures that could both alter performance.

The familiarisation session and experimental trials were separated by a minimum of three days to eliminate the potential effects of the second window of protection caused by IPC (Bolli 2000), and a maximum of seven days. All trials were performed at the same time of day for every participant to avoid potential circadian rhythms of physiological functions. The temperature was maintained constant throughout all trials (20.3 ± 0.4 °C).

Exercise protocol

The exercise protocol started 18 ± 2 minutes after the end of the last cycle of compression. Participants were seated in an upright position on the isokinetic dynamometer, and a strap was secured tightly across the pelvis. The right leg was fixed to the dynamometer with a strap above the ankle external malleoli, and the axis of rotation was aligned to the lateral femoral condyle of the knee joint.

The exercise protocol consisted of five sets of 5 maximum voluntary knee extensions (60° range of motion from 80° to 20° ; 0° corresponding to knee fully extended) at $20^\circ/\text{second}$ angular velocity (one extension lasting ~ 3.0 seconds). Participants were instructed to contract as hard as they could throughout the extension, and were strongly encouraged during all contractions. Contraction stopped during flexion when the dynamometer arm automatically returned to 80° at $120^\circ/\text{second}$ angular velocity (lasting less than 0.5 seconds), and started immediately after the return of the arm. Subjects rested quietly and relaxed for 30 seconds between each set. After the exercise, participants moved back to the bed to perform an arterial occlusion at 200 mmHg (~ 3 to 5 minutes) to obtain a physiological calibration of the NIRS signals. The cuff pressure was released after the deoxy-haemoglobin signal had reached a plateau (see Near-infrared spectroscopy section).

The force produced by participants was measured with a force transducer connected at the end of the level arm of the dynamometer, which was calibrated according to the manufacturer's recommendations before every trial (manufacturer typical error 0.5%).

The intra- and inter-day coefficient of variation for force obtained by the main experimenter was 2.4%. Force signals were analysed in Matlab[®] between a starting point defined when velocity was $\geq 18^\circ/\text{second}$, angle was $\geq 80^\circ$ and force was $\geq 100\text{N}$, and an end point when velocity was $\geq 18^\circ/\text{second}$ and angle was $\geq 20^\circ$. In every set, peak and average force were calculated. Total force was then calculated as the sum of the average force produced in all sets. Percent force decrement across all sets was calculated as follows: $100 - ([\text{total force output} / \text{ideal force output}] \times 100)$, where total and ideal force outputs are the sum of average force values from all sets and the highest average force was multiplied by five, respectively.

Near-infrared spectroscopy

During the entire protocol, muscle blood volume and oxygenation were assessed using a portable NIRS apparatus (PortaMon, Artinis medical systems BV, Netherlands). The NIRS device was installed on the distal part of the right vastus lateralis belly (approximately 15 cm above the proximal border of the patella). Skinfold thickness was measured at the site of application of the NIRS (9.0 ± 2.9 mm) using Harpenden skinfold calliper (Harpenden Ltd) during the familiarisation session, and was less than half the distance between the emitter and the detector (i.e., 20 mm). This thickness is adequate to let near-infrared light through muscle tissue (McCully and Hamaoka 2000). The skin was cleaned with an alcohol pad, and the device was fixed using double-sided stick disks and tape. Black bandages covered the device to eliminate background light. The position was marked with an indelible pen for the subsequent visit. The pressure cuff was positioned

above the NIRS device, which did not affect the placement of the device during occlusions.

A modified form of Beer-Lambert law, using two continuous wavelengths (760 and 850 nm) and a differential optical path length factor of 4.95, was used to calculate micromolar changes in tissue oxy-haemoglobin ([HbO₂]), deoxy-haemoglobin ([HHb]) and total haemoglobin ([THb] = [HbO₂] + [HHb]), which is used as an index of change in regional blood volume (van Beekvelt et al. 2001).

The NIRS data were acquired at 10Hz. At rest, baseline values of one minute were taken pre IPC and SHAM treatments. Then, NIRS signals were again collected at rest for one minute post treatments to assess the impact of IPC on resting blood volume (resting $\Delta[\text{THb}] = [\text{THb}]_{\text{post-treatment}} - [\text{THb}]_{\text{baseline}}$, μM). During exercise, NIRS analysis was limited to [HHb] since this variable is less sensitive than [HbO₂] to perfusion variations and abrupt blood volume changes during contraction and recovery (De Blasi et al. 1993; Ferrari et al. 2004). [HHb] was averaged over the last second ($\Delta[\text{HHb}]_{\text{peak}}$) and over 15 seconds ($\Delta[\text{HHb}]_{\text{avg}}$) in every set. These data were normalized to express the magnitude of changes from the baseline, and were expressed in percentage of the maximal amplitude calculated during an arterial occlusion performed at end-exercise. During recovery periods between exercise sets, the muscle reoxygenation rate (ΔReoxy , $\mu\text{M}\cdot\text{s}^{-1}$) was calculated as the rate of change in [HHb] from the end of the exercise set to the end of the subsequent recovery period (i.e., the recovery of [HHb]). During this period, we also examined the amplitude of change in [THb] ($\Delta[\text{THb}]_{\text{rec}}$).

Statistical analysis

All data are reported as means \pm standard deviation (SD) or percentage changes from SHAM. The IPC-SHAM differences were analyzed using Cohen's effect sizes (ES) \pm 90% confidence limits, and magnitude-based inferences (Batterham and Hopkins 2006; Hopkins et al. 2009). We used this qualitative approach because traditional statistical approaches often do not indicate the magnitude of an effect, which is typically more relevant to athletic performance than any statistically significant effect. Except for percent force decrement data, all variables were log-transformed prior to analysis (Hopkins et al. 2009). The chance that the true (unknown) performance or physiological variables were greater (i.e., greater than the smallest practically important effect), or the smallest worthwhile change (0.2 multiplied by the between-subject SD, based on Cohen's ES principle), similar or lower in IPC were calculated. Standardised effects were classified as small (>0.2), moderate (>0.5) or large (>0.8). Quantitative chances of greater or smaller values were assessed qualitatively as follows: 75% to 95%, likely; 95% to 99%, very likely; $>99\%$, almost certainly. If the chance of having better/greater or poorer/lower performances or physiological variables were both $>5\%$, the true difference was assessed as unclear (Batterham and Hopkins 2006; Hopkins et al. 2009).

Results

All 10 participants completed the entire protocol, met all criteria for occlusion and tolerated the IPC procedure without complications.

Performance

Values for peak, total, and average force are presented in Table 1, and Figures 1 and 2, respectively. The IPC manoeuver almost certainly increased peak force (on average 11.8% improvement, ES 0.37, 90% confidence limits for ES 0.27;0.47, Table 1) and total force (12.6%, ES 0.47, 0.29;0.66, Figure 1) compared with SHAM. Specifically, IPC produced almost certainly higher average force in the first (15.1%, ES 0.58, 0.37;0.80, Figure 2) and second sets (15.1%, ES 0.58, 0.36;0.80), and very likely higher average force in the third (11.3%, ES 0.44, 0.24;0.64) and fourth sets (13.9%, ES 0.54, 0.27;0.80). The change in average force in the fifth set was possibly higher in IPC (7.3%, ES 0.29, 0.04;0.55). Differences for percent decrement between IPC and SHAM were unclear (7.4%, ES 0.15, -0.45;0.74, Table 1).

Insert Table 1, Figures 1 and 2 about here

Muscle haemodynamics and oxygenation

No clear difference was observed between conditions for NIRS variables during baseline collected before the manoeuver. Immediately after the three conditioning cycles, IPC likely increased resting muscle blood volume ($\uparrow\Delta[\text{THb}]$, 46.5%, ES 0.56, -0.21;1.32, Figure 3A). Changes in blood perfusion during the recovery periods between sets are displayed in Figure 3B. $\Delta[\text{THb}]_{\text{rec}}$ was higher in IPC after set one (23.6%, ES 0.30, -0.05;0.65) and five (25.1%, ES 0.32, 0.09;0.55). The changes observed during the other recovery periods were not meaningfully different between conditions. Despite higher blood volume in IPC, the greater changes in ΔReoxy in IPC (Table 1) were not meaningfully different than in SHAM.

Insert Figure 3 about here

Changes in muscle $[\text{HHb}]_{\text{avg}}$ and $[\text{HHb}]_{\text{peak}}$ during the five exercise sets are displayed in Figure 4A and 4B, respectively. Overall, $\Delta[\text{HHb}]_{\text{avg}}$ (15.8%, ES 0.36, -0.07;0.79) and $\Delta[\text{HHb}]_{\text{peak}}$ (11.5%, ES 0.37, -0.17;0.90) were both possibly higher in IPC compared to SHAM. Specifically, average muscle O_2 extraction was likely improved during the first set of exercise (43.6%, ES 0.36, -0.05;0.77), but the changes were unclear in others sets. $\Delta[\text{HHb}]_{\text{peak}}$ was possibly higher during the second (10.7%, ES 0.36, -0.19;0.92, Figure 4B) and third sets (11.7%, ES 0.40, -0.19;0.99), and was likely higher in the fourth set (15.7%, ES 0.52, -0.07;1.12).

Discussion

This study examined the impact of IPC on skeletal muscle vasoactive and oxidative responses to maximal exercise with impeded muscle blood flow. The major findings were that three cycles of IPC at 200 mmHg activate the peripheral component of O_2 uptake and increase muscle perfusion at rest and during recovery periods between exercises sets more than a SHAM condition (20 mmHg). These haemodynamic and metabolic changes improved force production over five repeated, maximal efforts in strength-trained athletes. This manoeuvre may therefore be used to enhance competitive performance, but also prior to exercise training in order to augment training stimulus and muscle adaptations.

These ergogenic effects on muscle force occurred in all athletes (Figure 1) and in every set of the protocol (Figure 2). This is in accordance with studies showing the benefits of

IPC (2%-4%) on competitive 100-m swim (Jean-St-Michel et al. 2011) and 5-km running time trials (Bailey et al. 2012a). The larger force improvement observed in our study (~12%) could be attributed, in part, to the fact that competitive performance is affected by several other factors (e.g., psychological determinants) than purely the potentiation of the neuromuscular function. The benefits on muscle force occurred rapidly (less than 20 min post-IPC), and were the greatest during the first set of contractions. This is also in keeping with the observation of higher peak and mean power outputs during the first three repetitions of a series of ten 6-s cycle sprints (Patterson et al. 2015). The greater muscle force in set 1 could be due to a potentiated anaerobic metabolism. Although we were unable to perform muscle biopsies in the current study, increased phosphocreatine production has been observed using ^{31}P MRS in recovery from an ischemic event (Andreas et al. 2011). In this perspective, it is important to note that the largest force was developed in set 1 when skeletal muscle deoxygenation (and therefore muscle O_2 uptake) was not maximal (Figure 4). This is in keeping with the concept of the O_2 deficit occurring at the onset of high-intensity exercise (Medbo et al. 1988). However, this is not a consensus. IPC failed to enhance performance during three 30-m land-based sprints (<5 s) (Gibson et al. 2013), and had no effect on the power output developed during five 6-s all-out cycling sprints compared with a placebo condition (Gibson et al. 2015). The varied IPC protocols make it difficult to reconcile the data among the different studies. Indeed, the cuff pressure used for placebo interventions may be high enough in some cases to elicit a physiological response, and thereby lessen the IPC-SHAM difference. Despite the greater initial force developed in the current study, and likely greater subsequent metabolic and ionic perturbations (Balsom et al. 1994; Glaister 2005), the

percent force decrement was not clearly different between conditions, suggesting the rate of neuromuscular fatigue development was preserved in the IPC condition (Patterson et al. 2015). Indeed, although IPC did not alter the rate of fatigue *per se*, the force produced by the athletes was higher in every set (Figure 2), suggesting not only greater force endurance capacity, but also potentially faster recovery between efforts. When short cycling sprints (Balsom et al. 1994; Smith and Billaut 2010; Smith and Billaut 2012; Billaut and Buchheit 2013) or maximal isokinetic contractions (Christian et al. 2014) are repeated with limited recovery (as were the contractions in the current study), O₂ delivery and utilisation become performance-limiting factors. Furthermore, isometric or slow, isokinetic contractions dramatically increase intramuscular pressure, and subsequently hinder blood flow and vascular conductance more than dynamic contractions (Saltin et al. 1998; Wigmore et al. 2004; McNeil et al. 2015). As such, we originally reasoned that since IPC promotes vasodilation and O₂ delivery (Enko et al. 2011), a greater impact on physiological functions and performance would be observed during an exercise that impedes blood flow to skeletal muscles. The data displayed in Figures 3A and 3B demonstrate a clear, positive impact of IPC on blood volume (and likely blood flow) at rest and, more importantly, during recovery periods between efforts (23%-46% higher blood volume in IPC compared with SHAM). Since skeletal muscle perfusion influences the development of peripheral muscle fatigue (Ganesan et al. 2014), our current data suggest that the increase in local blood volume before and during exercise likely contributed to performance improvement (Padilla et al. 2011). An increased blood volume possibly accelerated ATP and PCr repletion, which are O₂ dependent (Kime et al. 2003), and removal of metabolic waste products during recovery periods between efforts

(Connolly et al. 2003; Glaister 2005). In fact, without measuring blood flow *per se*, IPC lowered blood lactate concentration after five 6-s sprints (Gibson et al. 2015). Along this line of reasoning, it was also reported that 220-mmHg IPC clearly benefited recovery of squat jump test and 10- and 40-m sprint performance 24 hours after an initial, fatiguing session (Beaven et al. 2012). However, despite improvement in muscle perfusion, the 3% greater muscle re-oxygenation rate measured in IPC in the current study was not meaningfully different than in SHAM. Thus, we cannot conclude that muscle tissue re-oxygenation contributed to the increased muscle force production in these normoxic conditions. Potentially, IPC could prove more beneficial in a hypoxic environment where the muscle re-oxygenation status appears critical to repeated maximal performance (Billaut and Buchheit 2013), which remains to be ascertained.

Insert Figure 4 about here

This IPC-induced hyperperfusion was accompanied by an increase in muscle O₂ extraction during contractions. The current study is the first to demonstrate an augmented tissue deoxygenation ($\uparrow\Delta[\text{HHb}]$) during repeated, maximal efforts, concomitant with enhanced muscle force, following IPC (Figure 4). Previous research using one bout of circulatory occlusion before the start of an exercise has demonstrated accelerated pulmonary O₂ uptake kinetics (Paganelli et al. 1989). Moreover, IPC has been shown to increase systemic maximal O₂ uptake (de Groot et al. 2010). All together, these data from various exercise modes demonstrate that IPC potentiates the oxidative response to exercise. Our results are concordant with the observation of greater tissue deoxygenation at task failure during handgrip exercise at 45% maximal voluntary contraction (Barbosa

et al. 2015). An interesting observation from the current study was that while $\Delta[\text{HHb}]_{\text{peak}}$ remained clearly elevated during contractions sets –indicating larger peak oxidative response in IPC–, the $\Delta[\text{HHb}]_{\text{avg}}$ was likely improved during the first set only, with unclear IPC-SHAM differences in subsequent sets. Based on these data, we speculate that IPC may improve the overall metabolic efficiency of muscle contraction (higher force developed with lower average O_2 uptake). Observations from studies of hypoxic exercise training (Faiss et al. 2013b) could shed some light on potential mechanisms at play during IPC. The combination of maximal intensity and slow, isokinetic contractions elevated intramuscular pressure, and likely reduced the O_2 availability to demand ratio, which is known to induce a compensatory vasodilation response to increase O_2 delivery to hypoxic tissues (Casey and Joyner 2012). With such high-intensity and metabolic conditions, type II muscle fibres are maximally recruited. It is therefore probable that type II fibres (typically displaying a lower microvascular O_2 partial pressure) benefited more than type I fibres from this increased blood perfusion (McDonough et al. 2005). In fact, the duration of IPC-induced ischemia necessary to induce ischemic tolerance was shown to be shorter (2.5 min vs. 5 min) in a fast- than in a slow-twitch skeletal muscle (Mattei et al. 2000). Based on our NIRS data and published literature, we speculate that IPC would induce acute beneficial adaptations mainly through an improved blood perfusion leading to enhanced O_2 extraction and improved resistance of type II fibres (Cleland et al. 2012). Such putative mechanism is supported by similar observations during adaptations to sprint training in hypoxia (Faiss et al. 2013a; Faiss et al. 2013b). Importantly, however, the time course of these physiological adaptations is much shorter in IPC (a few minutes of ischemia/reperfusion) than training in hypoxia (typically a few weeks). Therefore, IPC

efficiency is likely to be fibre-type specific and intensity dependent, and based on mechanisms presumably similar to those associated with sprint training in hypoxia (Faiss et al. 2013a; Faiss et al. 2013b).

An important consideration when using IPC is the minimal restrictive cuff pressure applied to the limb required to occlude arterial blood flow since it affects intramuscular pressure and the magnitude of subsequent physiological responses. Thigh circumference is a strong determinant of this pressure, and it has been concluded from 116 healthy participants that a cuff width of 13.5 cm occludes arterial flow at 144 ± 17 mmHg (Loenneke et al. 2012). However, to our best knowledge, there is no published scale of pressure to use for a given limb circumference, so it is still currently very difficult to ascertain the “right” pressure for every subject. To reduce this potential methodological limitation in the current study, we used a 21-cm cuff and a pressure of 200 mmHg in all participants. Although we cannot exclude the impact of a standardised pressure on individual physiological responses, we are confident that the pressure we used successfully occluded the limb since all participants displayed a plateau in NIRS-derived deoxygenated haemoglobin concentration and tissue saturation index within 2 to 4 min during the first IPC cycle. Furthermore, this approach successfully increased force in all participants, compared with SHAM (Figure 1), regardless of the actual level of occlusion achieved.

In conclusion, the current study demonstrated that three cycles of 200-mmHg IPC enhanced muscle force during slow, isokinetic, maximal contractions in strength-trained

athletes more than a 20-mmHg SHAM condition. This ergogenic effect was mediated by increases in muscle perfusion and capacity to extract O₂. This improved metabolic efficiency is probably dependent upon the compensatory vasodilatory effects on the behaviour of type II muscle fibres. Further research with large sample sizes and double-blinded protocols is warranted to ascertain the impact of IPC on fibre recruitment and its efficacy as a preconditioning routine to enhance training adaptations.

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Conflict of interest disclaimer

The authors declare that there are no conflict of interest.

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Table**Table 1:** Performance, muscle haemodynamic and oxygenation measures in IPC and SHAM conditions.

	SHAM	IPC	% difference (ES) \pm 90% CL
Peak force S1 (N)	598.5 \pm 157.7	655.9 \pm 137.3***	10.9% ES 0.34, 0.21;0.46
Peak force S2 (N)	541.2 \pm 119.0	612.9 \pm 176.3**	11.3% ES 0.35, 0.15;0.54
Peak force S3 (N)	530.6 \pm 134.7	555.7 \pm 143.5*	5.0% ES 0.34, 0.02;0.29
Peak force S4 (N)	504.5 \pm 108.9	544.4 \pm 155.0*	6.2% ES 0.34, -0.03;0.42
Peak force S5 (N)	486.7 \pm 102.3	518.0 \pm 137.8*	5.3% ES 0.34, -0.03;0.37
Percent decrement	14.1 \pm 7.7	15.8 \pm 6.6	-7.4% ES 0.15, -0.45;0.74
Δ Reoxy ($\mu\text{M}\cdot\text{s}^{-1}$)	0.23 \pm 0.19	0.25 \pm 0.20	3.0% ES -0.06, -0.43;0.30

Compared with the SHAM condition: *: possibly, **: likely, ***: very likely clear effects. Values are mean \pm SD. Δ Reoxy: reoxygenation rate of the muscle, S: sets.

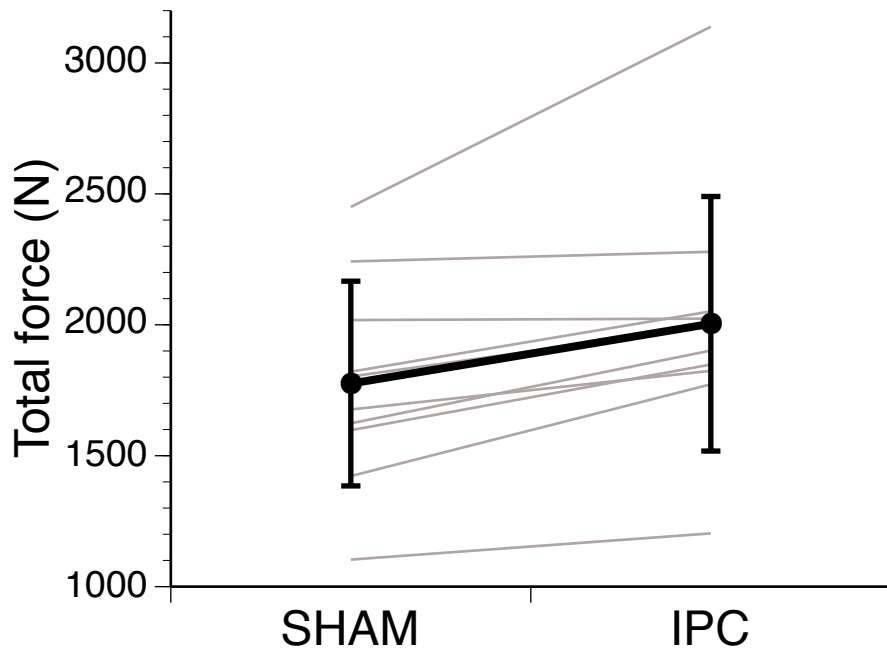
Figure captions

Figure 1: Individual (—) and mean (—) total force developed in SHAM and IPC conditions. Mean values are mean \pm SD.

Figure 2: Average force produced during the five sets in SHAM (■) and IPC (○) conditions. Compared with SHAM condition: #### almost certainly moderate effect, ## very likely moderate effect, ** very likely small effect, * possibly small effect. Values are mean \pm SD.

Figure 3: Changes in resting total haemoglobin concentration ([THb]) from baseline to post-SHAM and IPC conditions (A), and changes in muscle blood volume amplitude (Δ [THb]_{rec}) during recovery periods between exercise sets (B) in SHAM (■) and IPC (○) conditions. Compared with SHAM condition: # likely moderate effect, ** likely small effect, * possibly small effect. Values are mean \pm SD.

Figure 4: Changes in average muscle O₂ extraction (Δ [HHb]_{avg}) (A) and peak muscle O₂ extraction (Δ [HHb]_{peak}) (B) during the exercise sets, expressed as a fraction of the maximal values obtained during a transient arterial occlusion in SHAM (■) and IPC (○) conditions. Compared with SHAM condition: ## likely moderate effect, ** likely small effect, * possibly small effect. Values are mean \pm SD.



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