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Original Research

Inter-Effort Recovery Intermittent Hypoxia and Force Parameters in Sprint Interval Exercise

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Abstract

International Journal of Exercise Science 18(3): 672-685, 2025. https://doi.org/10.70252/EDSR9101 Performing training sessions in hypoxia leads to a decrease in effort quality. The inter-effort recovery intermittent hypoxia model seems to ensure training session performance. The aim of this study is to investigate the effects of sprint interval exercise under normoxic (NOR), continuous hypoxic (HYP), and inter-effort hypoxic (IEH) conditions on force parameters. Seven swimmers (age: 26.04 ± 4.64 years) volunteered and performed one session of the 10 × 30-s all-out tethered swimming efforts with 4-min passive recovery intervals for each condition. Considering the simulated altitude at F_iO_2 = 0.13 and NOR at F_iO_2 = 0.209. The sessions were separated at least 48 hours. The peak force (PF), mean force (MF), impulse, fatigue index (FI) and percentage mean force relative to peak force (PF_{PERC}) were determined for each effort. The force parameters were higher on IEH (PF: Δ = 21.32 N; MF: Δ = 9.65 N; impulse: Δ = 626.78 N·s) and HYP (PF: Δ = 15.80 N; MF: Δ = 6.92 N; impulse: Δ = 621.77 N·s) in relation of the NOR ($p < 0.001$). PF_{PERC} evidenced lower values in IEH in relation to HYP (Δ= 3.1 %, $p = 0.017$). The HYP and IEH condition can be considered a model that enhances performance in force parameters compared to the NOR condition.

Keywords: Normobaric hypoxic, tethered swimming, oxygen saturation, sports science, training performance

Introduction

There are different training models associated with hypoxic conditions, both natural and simulated,[1-3] and the intermittent hypoxic training (IHT) model has gained prominence due to the physiological benefits observed under this condition and for allowing the simulation of altitude.[4,5] This model involves performing efforts and rest in hypoxia. Most studies have found changes in physical and sports performance resulting from the stabilization of HIF-1α (Hypoxia-inducible factor 1-alpha), leading to hematological and non-hematological changes, such as increased erythropoietin hormone levels, increased activity of glucose transporters,[6-8] and transcription of genes that affect the function of skeletal muscle tissue[7]. However, IHT does not always lead to improved sports performance.[9-11] A major common limitation is the quality (i.e. intensity) of training. Since efforts are made under hypoxic conditions, there are reports of reduced average sprint intensity, decreased total work, and worsened motor patterns compared to efforts in normoxia.[12] In this sense, performing efforts in hypoxic conditions in swimmers can be more detrimental, as reduced oxygen levels combined with fatigue may result in decreased technical quality and propulsive swimming force, which are crucial for success in short-duration events.

Based on this context, studies have gone further and proposed a new approach to incorporating hypoxia into sports training. The model called inter-effort recovery hypoxia (IEH) is an adapted version of IHT, meaning hypoxia is applied during the recovery intervals between high-intensity interval training efforts to maintain training quality and enhance sports performance.[13-15] The first known study to investigate this model in cyclists over seven weeks, with sessions twice a week, found no changes in hematological parameters or performance, except for an increase in VO_{2max} in the IEH group.[14] An acute study using the IEH model, consisting of interval running training at 110% of VO_{2max} intensity (iVO_{2max}), did not find significant differences in blood lactate and glucose values, even though SpO_2 and heart rate showed differences.[15] De Carvalho et al[13] did not find differences in blood lactate and heart rate values during interval running training at 120% of iVO_{2max}, even though the IEH had a higher dose of hypoxia than that traditionally used in IHT. Unlike the other studies, this last one stands out due to the monitoring of internal load through rate of perceived exertion during the training session, and no significant differences were observed between normoxic training and IEH for this variable, supporting the hypothesis that this model maintains training quality.

Although these studies confirm the additional stimulus potential of IEH and its protective role in maintaining training quality, these results have raised questions regarding the physiological behavior observed with IEH. Considering the physiological changes triggered by exposure and the dose of hypoxia required for beneficial changes, theoretically, IEH should have shown differences in hematological parameters, blood lactate and glucose concentrations, as well as heart rate, compared to normoxic conditions. It is worth noting that these studies share a common limitation, that is the lack of comparison with training conducted entirely in continuous hypoxia, which may result in divergent behaviors. However, the researchers Li, Anbalagan, Pang, Ihsan and Girard[16] recently investigated different modulations in oxygen availability, including continuous hypoxic, on the performance of repeated sprints in cycling and found that mechanical performance is affected by a decrease in oxygen supply, without altering perception responses between hypoxic conditions.

According to the importance of maintaining performance in repeated sprints in different conditions and the limitation of comparisons with the normobaric continuous hypoxic condition in swimming, the objective of this study is to investigate the effects of sprint interval exercise under normoxic (NOR), continuous hypoxic (HYP), and IEH conditions on physiological parameters and propulsive force in swimmers. The hypothesis is that the IEH model will show advantages compared to the other conditions and serve as an alternative to enhance training programs in swimming.

Methods

Participants

The minimum sample size was calculated using G*Power 3.1 software (Düsseldorf, Germany). The sample power was determined a priori, assuming an alpha error of 5%, a beta error of 80%, and an effect size of 1.3, based on brachial artery values reported in the study by Willis, Peyrard, Rupp, Borrani and Millet.[17] In this statistical model, a minimum of eight participants is required (critical F = 5.98, power = 0.97). Initially, nine swimmers were recruited. By the end of the experiments, two samples were lost due to injuries and scheduling conflicts. Thus, seven recreational-level swimmers,[18] who completing at least 150 to 300 min moderate-intensity activity or 75–150 min of vigorous-intensity activity a week, plus muscle-strengthening activities 2 or more days a week, voluntarily participated in this study.

Anthropometrical measures were obtained through dual-energy X-ray absorptiometry, and participants' characteristics are shown in Table 1. The inclusion criteria included low-landers swimmers with at least three years of swimming experience, who had no recent history of anemia diagnosis, no recent muscular injuries, and no prior exposure to normobaric or hypobaric hypoxia. The experimental procedures were approved by the Institutional Research Ethics Committee (protocol number: 64691620.0.0000.5659) and conducted in accordance with the Declaration of Helsinki[19] after obtaining written informed consent from all participants and the ethical standards of the *International Journal of Exercise Science*.[20]

Table 1. Mean ± standard deviation of participants' characteristics.

	All (*n* = 7)	Male (*n* = 5)	Female (*n* = 2)
Age (years)	26.04 ± 4.64	25.24 ± 4.43	28.05 ± 6.29
Height (cm)	170.14 ± 10.27	175.00 ± 6.52	158.00 ± 7.07
Fat mass (kg)	17.73 ± 8.51	15.10 ± 8.71	24.30 ± 3.20
Lean mass (kg)	53.02 ± 13.84	58.88 ± 10.93	38.38 ± 8.49
Total body mass (kg)	73.64 ± 17.50	77.16 ± 19.22	64.85 ± 11.95

Protocol

To investigate the effects of inter-effort recovery intermittent hypoxia on propulsive swimming forces and physiological responses in sprint interval exercise, a double-blind, randomized, cross-over, controlled trial was performed. After a familiarization period, participants attended the laboratory on three different days, with each visit 48 hours apart. The assessments were conducted on a sprint interval exercise, randomly performed under normoxia (F_iO_2 = 0.209), continuous hypoxia (F_iO_2 = 0.13), and inter-effort recovery intermittent hypoxia conditions (effort F_iO_2 = 0.209 and interval recovery F_iO_2 = 0.13). The sprint interval exercise protocol was characterized by 10 × 30-s all-out tethered front crawl swimming efforts with 4-min passive recovery intervals. During the sessions, swimming forces were recorded in each effort, and peripheral oxygen saturation, heart rate, blood lactate, and rate of perceived exertion were assessed at 1-min time point during each recovery period. The experimental design is schematized in the Figure 1.

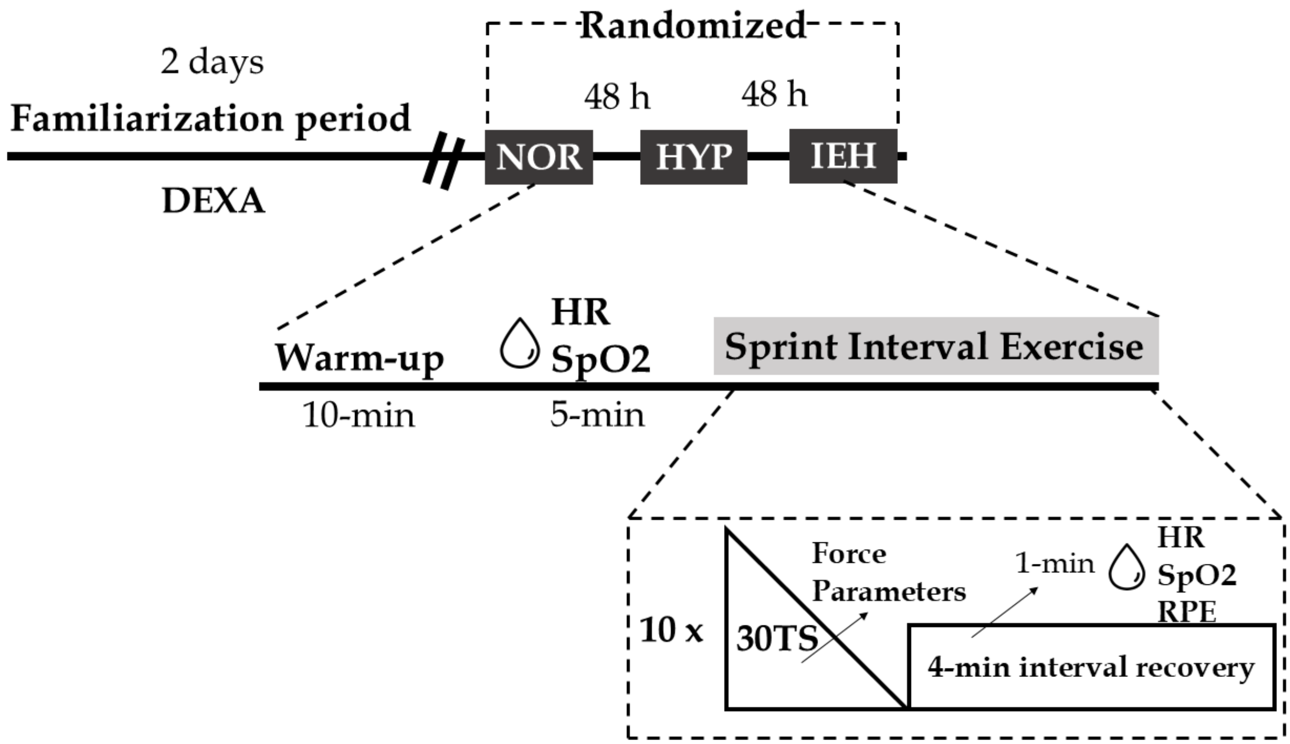

Figure 1. Schematic of the experimental design and exercise session. After familiarization period and the determined body composition (dual-energy X-ray absorptiometry – DEXA) the exercise sessions conditions were randomized and separated for at least 48-h. The sessions were composed for 10 sprints of the 30-s all-out tethered front crawl swimming efforts with 4-min passive recovery intervals. The force parameters were collected during each effort and physiological parameters were collected after warm-up and 1-min time point of the passive intervals. NOR: normoxic condition; HYP: continuous hypoxic condition; IEH: inter-effort hypoxic condition; Red drop: 25-µL blood samples; HR: heart rate; SpO_2: peripheral oxygen saturation; RPE: rate of perceived exertion; 30TS: 30-s all-out tethered front crawl swimming efforts.

To induce the participants into normoxia, continuous hypoxia, or inter-effort recovery intermittent hypoxia conditions during the exercise sessions, a hypoxic generator (CAT 430 TM, Altitude Control Technologies, USA) attached to a hermetically sealed air storage system[21] was used to set the FiO_2 at 20.9% for normoxic and 13.4% for hypoxic conditions. The air supply was delivered through a one-way valve connected to a hose deriving from the air storage system,[21] which was integrated with the swimmers via a front snorkel with a purge valve (Mares Diving Snorkel, Nabaiji®). To avoid compromising swimming technique, the hose was vertically supported by a 2-m high steel cable fixed parallel to the swimming pool, at the location where the swimmers were positioned during the 30-s tethered efforts. The hypoxia exposure procedures are schematized in the Figure 2.

During the exercise sessions, participants continuously used the snorkel both during the 30-s efforts and the 4-min recovery periods. Normoxia and continuous hypoxia conditions were characterized by continuous air supply (i.e., during both effort and recovery periods) fixed at FiO_2 of 20.9% and 13.4%, respectively, while in the inter-effort recovery intermittent hypoxia condition the FiO_2 was fixed at 20.9% during the efforts and 13.4% during the recovery intervals.

In this way, the change in FiO_2 from 20.9% to 13.4% after the efforts, and from 13.4% to 20.9% after recoveries, were made immediately at the end of the 30-s efforts and at 30 seconds remaining until the next effort (during recovery periods), respectively. To rapidly change the FiO_2 values, a PVC ball valve system was used hidden from the researchers and participants to prevent them from identifying the session condition, ensuring a double-blind design. To achieve this, only a single researcher was responsible for the random assignment of conditions and the management of the PVC valve and air storage systems during the experimental procedures.

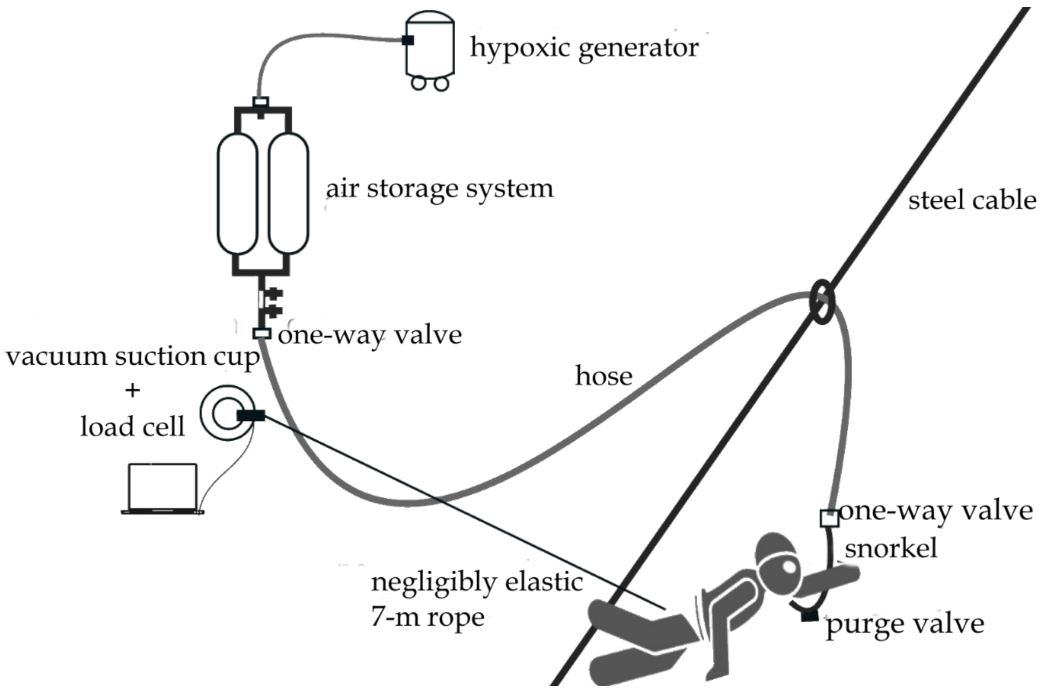

Figure 2. Schematic of the hypoxia exposure and tethered swimming apparatus. A hypoxic generator supply air system that was connected to the snorkel with a purge valve through a hose with a one-way valve attached at each end. A steel cable was necessary for the hose to remain suspended. A vacuum suction was fixed on the wall and connected to a load cell. A negligibly elastic rope tied to load cell and a nylon belt allowed the swimmer to realize the efforts in tethered swimming.

The sprint interval exercise was characterized by a 10-min low-paced freestyle warm-up followed by 10 × 30-s all-out tethered front crawl swimming efforts with 4-min passive recovery intervals. After the warm-up, participants put on the snorkel derived from the air storage system and were tied to a negligibly elastic 7-m rope by a nylon belt, connected to a load cell attached to a vacuum suction cup fixed on the wall at approximately 60 cm above the ground, and then researchers started the exercise protocol (Figure 2). Throughout the session, five seconds before the start of each effort, the participants were instructed to remain floating in a prone position with the rope fully stretched, allowing the start of the 30-s maximal effort to be signaled audibly. During the efforts, swimmers arbitrarily chose their stroke frequency and breathing pattern, and all were instructed and verbally encouraged to give maximum effort. The exercise protocol was conducted in a short-course indoor pool (25 m long × 12 m wide) at a temperature of 29 ± 1 °C. All participants were advised to avoid caffeine, alcohol, or energy drinks for at least 12 hours before each session.

The 30-s tethered swimming protocol was performed as previously proposed[22]. The force-time curves of each 30-s effort were acquired at 1000 Hz using a load cell (CSR-50kg, MK Controle, SP, BRAZIL), amplified by an analog signal amplifier (MKTC05, MK Control and Instrumentations), and recorded by the data acquisition board (USB-6009, National Instruments) using LabView™ software (version 15.0, National Instruments). Subsequently, the data were processed in a MATLAB software (R2018a version 9.4.0, The MathWorks) with a 15 Hz Butterworth filter for the calculation of peak force, mean force, impulse (force-time integral), and fatigue index percentage ([peak force−minimum force] × 100/peak force). In addition, the percentual of mean force relative of the peak force (PF_{PERC}) was calculated in each effort and assumed the mean for each condition. To convert the signals collected in volts into newtons, a calibration protocol based on a simple linear regression was performed before each session by applying six progressively known weights ranging from 0.1 to 10.2 kg, matched with the average voltage recorded over 10 seconds.

During the 4-min recovery intervals, at 1-min of each interval, peripheral oxygen saturation and heart rate values were recorded using a fingertip oximeter (OX-06 HC261, Multilaser), the lactate concentration was determined by means of 25-µL blood samples collected from the earlobe using glass heparinized capillary microtubes, immediately dispensed and homogenized in Eppendorf tubes containing 1% sodium fluoride (NaF), which were stored at –12 ºC and later analyzed using a YSI 2300 STAT lactate analyzer (Yellow Springs, OH, USA) and the rate of perceived exertion was recorded using the Borg CR10 RPE scale.[23] Training impulse (TRIMP) was determined by the product the means values of physiological intensity markers (i.e., heart rate and blood lactate) and RPE by the training volume (duration of each session in minutes) and assumed as internal training load.[24,25]

Statistical Analysis

Data dispersion was analyzed using box-plot graphs and histograms. Outliers were identified based on 1.5 standard deviations and retained in the analyses after through data validation. A generalized linear mixed model (GLMM) with a gamma distribution was used to compare the dependent variables. Time (BL × E1 to E10) and conditions (NOR × HYP × IEH) were set as fixed effects, subjects set as random effects, and type I error set at $a < 0.05$. No covariates were used for model, and results are reported as estimated marginal mean (95% lower – 95% upper confidence interval) for sessions and estimated marginal mean ± 95% confidence interval for efforts. The differences between parameters were analyzed using the Bonferroni *post-hoc* multiple comparisons set at $p_{Bonf} < 0.05$, and effect sizes were reported as Cohen's d (0 to 0.2 = small, 0.2 to 0.5 = medium, 0.5 to 0.8 = large and > 0.9 = very large)[26]. All analyses were performed in R Studio (R Core Team, 2023) with the GAMLj package[27] and the effect size was calculated using the ration of the differences between means conditions and the standard deviation.[26]

Results

Tethered swimming force results are shown in Table 2. Differences between conditions evidenced higher values in IEH and HYP in relation to NOR for peak force (IEH: $\Delta = 21.32$ N, p

< 0.001, $d = 0.41$; HYP: $\Delta = 15.80$ N, $p < 0.001$, $d = 0.33$), mean force (IEH: $\Delta = 9.65$ N, $p < 0.001$, $d = 0.39$; HYP: $\Delta = 6.92$ N, $p < 0.001$, $d = 0.31$), impulse (IEH: $\Delta = 626.78$ N·s, $p < 0.001$, $d = 1.03$; HYP: $\Delta = 621.77$ N·s, $p < 0.001$, $d = 1.12$), and lower values for fatigue index (IEH: $\Delta = -11.44$ %, $p < 0.001$, $d = -1.36$; HYP: $\Delta = -12.45$ %, $p < 0.001$, $d = -1.71$). Only PF_{PERC} evidenced lower values in IEH in relation to HYP ($\Delta = 3.1$ %, $p = 0.017$, $d = -0.48$).

Table 2. Estimated marginal means (95% lower – 95% upper confidence interval) of tethered swimming force parameters of sprint interval exercise under normoxia, continuous hypoxia and inter-effort recovery intermittent hypoxia conditions.

	NOR	HYP	IEH
PF (N)	168.24 (129.45 – 207.02)	184.04 (145.21 – 222.87) [a]	189.56 (150.69 – 228.42) [a]
MF (N)	64.96 (47.27 – 82.64)	71.87 (54.16 – 89.59) [a]	74.61 (56.88 – 92.33) [a]
IMP (N·s)	1296.98 (1153.05 – 1440.91)	1917.90 (1759.30 – 2076.50) [a]	1923.76 (1772.81 – 2074.72) [a]
FI (%)	75.93 (70.65 – 81.21)	63.47 (58.29 – 68.66) [a]	64.49 (59.29 – 69.68) [a]
PF_{PERC} (%)	36.8 (30.9 – 42.8)	38.6 (32.6 – 44.6)	35.5 (29.6 – 41.4) [b]

NOR: normoxia condition; HYP: continuous hypoxic condition; IEH: inter-effort recovery intermittent hypoxia condition; PF: peak force; MF: mean force; IMP: impulse; FI: fatigue index; PF_{PERC}: percentual of mean force relative of the peak force performed in each condition. [a] denotes difference of normoxia condition ($p_{Bonf} < 0.05$). [b] denotes difference of continuous hypoxic condition ($p_{Bonf} < 0.05$).

Tethered swimming force parameters for each effort during the sprint interval exercise are shown in Figure 3. *Post-hoc* multiple comparisons evidenced differences for impulse, but not for peak force, mean force, and fatigue index. Under IEH condition, the impulse was lower in the fourth ($\Delta = 367.54$ N·s, $p_{Bonf} < 0.001$, $d = -0.54$), and from seventh to tenth in relation to first effort ($\Delta_{mean} = 400.85$ N·s, $p_{Bonf} \leq 0.001$, $d \geq -0.75$); and in the eighth and ninth in relation to second effort ($\Delta_{mean} = 415.61$ N·s, $p_{Bonf} \leq 0.025$, $d \geq -0.71$) effort. For HYP condition, the sixth effort was smaller compared to the first and second efforts ($\Delta_{mean} = 369.24$ N·s, $p_{Bonf} \leq 0.019$, $d \geq -0.34$). No differences were observed under NOR condition.

Physiological responses are shown in Table 3. Differences between conditions showed lower levels of peripheral oxygen saturation both in IEH and HYP in relation to NOR condition (IHE: $\Delta = -14.51$ %, $p < 0.001$, $d = -1.86$; HYP: $\Delta = -13.01$ %, $p < 0.001$, $d = -1.74$). In addition, higher heart rate values were found in IEH compared with both HYP ($\Delta = 7.77$ bpm, $p = 0.007$, $d = -0.34$) and NOR ($\Delta = 8.01$ bpm, $p = 0.004$, $d = -0.44$) conditions. No differences were observed for blood lactate concentrations and rate of perceived exertion.

Physiological responses of each effort during the sprint interval exercise are shown in Figure 4. *Post-hoc* multiple comparisons showed lower peripheral oxygen saturation for IEH in forth ($\Delta = -22.75$ %, $p_{Bonf} < 0.027$, $d = -2.39$) and five ($\Delta = -23.68$ %, $p_{Bonf} = 0.016$, $d = -1.579$) efforts in relation to tenth effort, and for HYP in sixth ($\Delta = 18.38$ %, $p_{Bonf} = 0.014$, $d = -1.667$) and eighth ($\Delta = -19.58$ %, $p_{Bonf} = 0.004$, $d = -1.668$) in comparison to tenth effort. No difference was found for NOR condition.

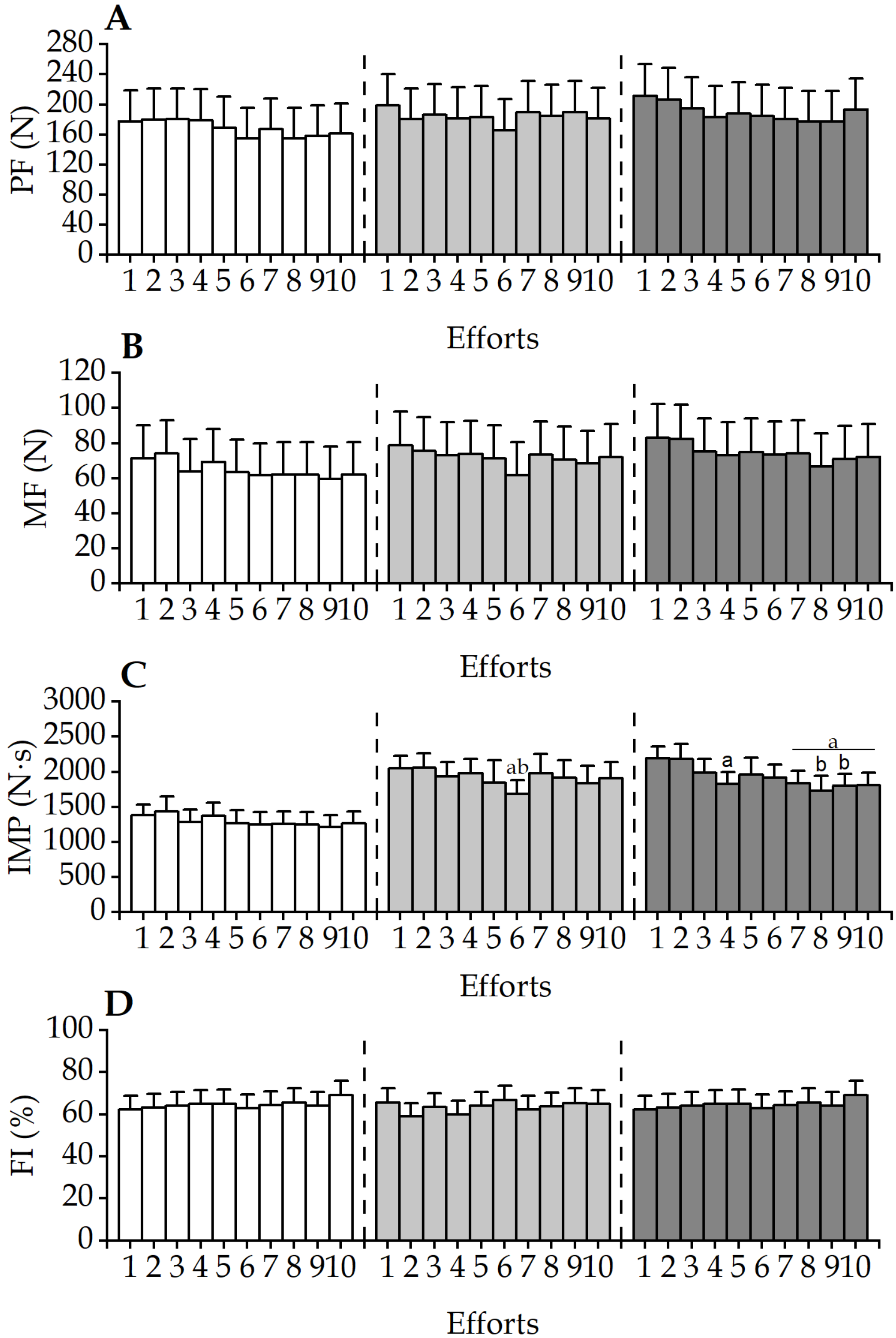

Figure 3. Estimated marginal means ± 95% confidence interval of **(A)** peak force, **(B)** mean force, **(C)** impulse, and **(D)** fatigue index. White, light gray, and dark gray bars represent normoxia, continuous hypoxia, and inter-effort recovery intermittent hypoxia conditions, respectively. [a] denotes difference of the first effort ($p_{Bonf} < 0.05$). [b] denotes difference of the second effort ($p_{Bonf} < 0.05$).

Table 3. Estimated marginal means (95% lower – 95% upper confidence interval) of physiological responses of sprint interval exercise under normoxia, continuous hypoxia and inter-effort recovery intermittent hypoxia conditions.

	NOR	HYP	IEH
SpO_2 (%)	94.12 (89.84 – 98-40)	81.11 (76.88 – 85.34) [a]	79.61 (75.30 – 83.91) [a]
HR (bpm)	131.84 (125.41 – 138.28)	132.09 (125.54 – 138.63)	139.85 (133.18 – 146.53) [ab]
$[La^-]$ (mM)	10.88 (9.17 – 12.59)	10.93 (9.22 – 12.64)	10.53 (8.83 – 12.24)
RPE (u.a)	7.19 (6.12 – 8.26)	7.16 (6.09 – 8.22)	7.53 (6.45 – 8.60)

NOR: normoxia condition; HYP: continuous hypoxic condition; IEH: inter-effort recovery intermittent hypoxia condition; SpO_2: peripherical oxygen saturation; HR: hearth rate; $[La^-]$: blood lactate concentration; RPE: rate of perceived exertion. [a] denotes difference of normoxia condition (p < 0.05). [b] denotes difference of continuous hypoxia condition (p < 0.05).

For blood lactate concentrations, IEH condition showed higher values in all efforts from second to tenth in relation to first effort (Δ_{mean} = 4.69 mM, $p_{Bonf} \leq 0.013$, $d \geq 2.02$). Under HYP condition, were also found higher values in all efforts from second to tenth in relation to first effort (Δ_{mean} = 5.63 mM, $p_{Bonf} \leq 0.001$, $d \geq 1.54$), and in eighth (Δ = 5.09 mM, $p_{Bonf} < 0.001$, $d = 2.16$) and ninth (Δ = 4.53 mM, $p_{Bonf} = 0.004$, $d = 1.57$) in relation do second effort. For NOR condition, all efforts from the second to tenth were greater than the first effort (Δ_{mean} = 6.06 mM, $p_{Bonf} \leq 0.001$, $d \geq$ 1.35), and from five to the tenth were higher to the second effort (Δ_{mean} = 3.95 mM, $p_{Bonf} \leq 0.034$, $d \geq 1.32$).

For rate of perceived exertion, IEH condition demonstrate higher values from seventh to tenth effort in relation to first effort (Δ_{mean} = 2.89 a.u., $p_{Bonf} \leq 0.005$, $d \geq 1.92$), from six to tenth in relation to second effort (Δ_{mean} = 2.84 a.u., $p_{Bonf} \leq 0.029$, $d \geq 1.21$), and in the tenth against the third (Δ = 2.52 a.u., $p_{Bonf} = 0.017$, $d = 1.75$) and fourth (Δ = 2.54 a.u., $p_{Bonf} = 0.015$, $d = 1.60$) efforts. For HYP, from the fifth to tenth effort there were differences compared to the first effort (Δ_{mean} = 3.03 a.u., $p_{Bonf} \leq 0.003$, $d \geq 1.98$), from the seventh to tenth differences to the second effort (Δ_{mean} = 2.83 a.u., $p_{Bonf} \leq 0.004$, $d \geq 1.58$), and from the eight to tenth differences to the third effort (Δ_{mean} = 2.64 a.u., $p_{Bonf} \leq 0.009$, $d \geq 1.62$). For NOR condition, in the fourth and from the six to tenth efforts were grater to first effort (Δ_{mean} = 2.90 a.u., $p_{Bonf} \leq 0.025$, $d \geq 1.37$), from seventh to tenth grater from second effort (Δ_{mean} = 2.71 a.u., $p_{Bonf} \leq 0.008$, $d \geq 1.46$), and tenth higher to third (Δ = 2.93 a.u., $p_{Bonf} = 0.001$, $d = 1.64$) and five (Δ = 2.68 a.u., $p_{Bonf} = 0.008$, $d = 1.56$) efforts.

Table 4. Estimated marginal means (95% lower – 95% upper confidence interval) of training impulse of sprint interval exercise under normoxia, continuous hypoxia and inter-effort recovery intermittent hypoxia conditions.

	NOR	HYP	IEH
$TRIMP_{HR}$ (u.a)	5932.78 (5649.55 – 6216.02)	5965.42 (5710.4 – 6220.39)	6329.39 (6066.86 – 6591.91) [ab]
$TRIMP_{[La-]}$ (u.a)	492.42 (394.86 – 589.97)	502.47 (404.31 – 600.62)	475.75 (378.47 – 573.03)
$TRIMP_{RPE}$ (u.a)	322.26 (272.84 – 371.67)	320.21 (270.81 – 369.60)	339.69 (289.91 – 389.48)

NOR: normoxia condition; HYP: continuous hypoxic condition; IEH: inter-effort recovery intermittent hypoxia condition; $TRIMP_{HR}$: heart rate-based training impulse; $TRIMP_{[La-]}$: blood lactate concentration-based training impulse; $TRIMP_{RPE}$: rate of perceived exertion-based training impulse. [a] denotes difference of normoxia condition (p < 0.001). [b] denotes difference of continuous hypoxia condition (p < 0.001).

Finally, training impulse results are shown in Table 4. A condition effect was found only in heart rate-based training impulse, evidenced higher values in IEH compared with both HYP (Δ = 363.97 a.u., $p_{Bonf} < 0.001$, $d = -1.07$) and NOR (Δ = 396.60 a.u., $p_{Bonf} < 0.001$, $d = -1.03$) conditions.

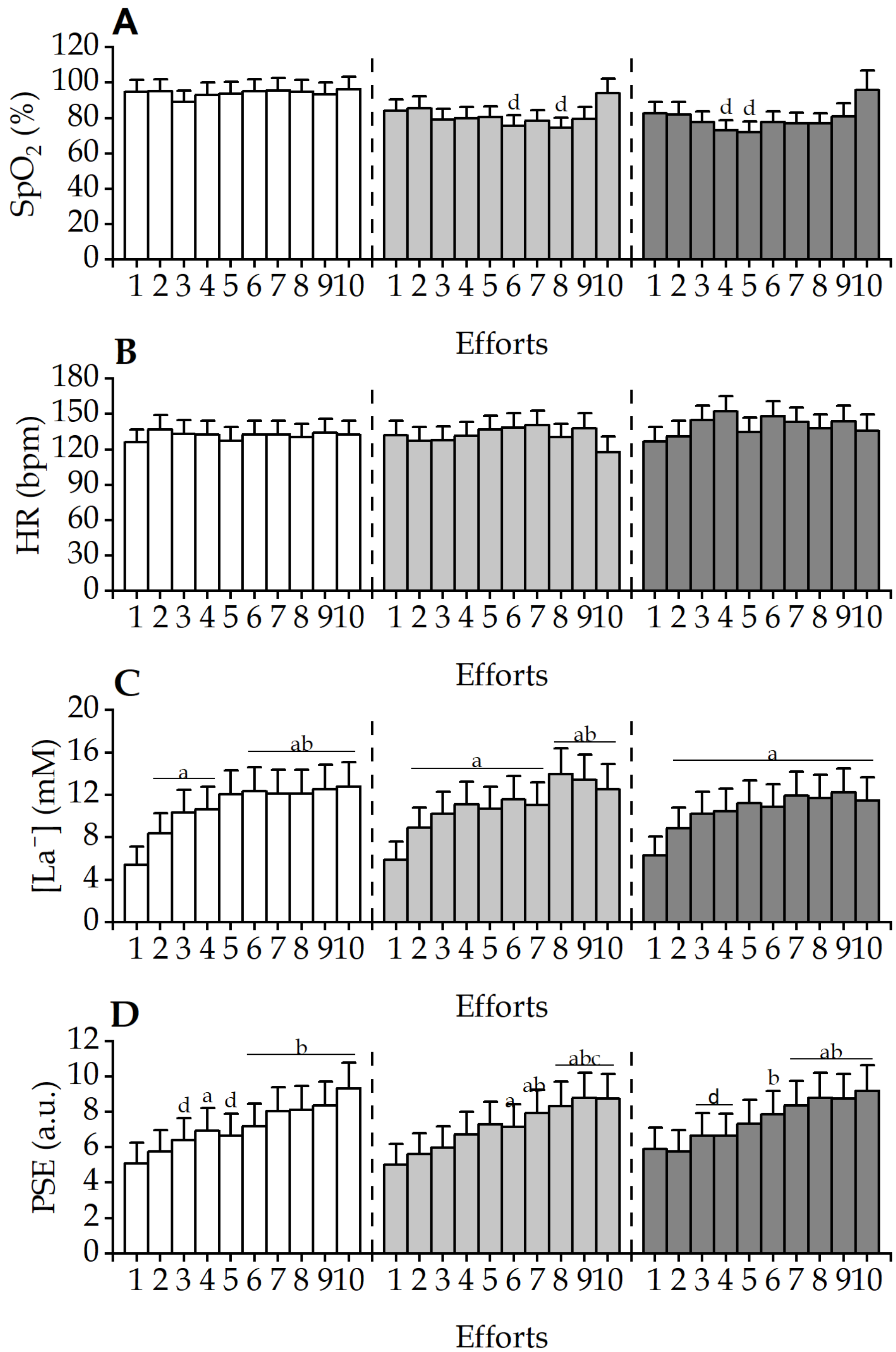

Figure 4. Estimated marginal means ± 95% confidence interval of **(A)** peripheral oxygen saturation, **(B)** heart rate, **(C)** blood lactate concentration, and **(D)** rate of perceived exertion. White, light gray, and dark gray bars represent normoxia, continuous hypoxia, and inter-effort recovery intermittent hypoxia conditions, respectively. [a] denotes difference of the first effort ($p_{Bonf} < 0.05$). [b] denotes difference of the second effort ($p_{Bonf} < 0.05$). [c] denotes difference of the third effort ($p_{Bonf} < 0.05$). [d] denotes difference of the tenth effort ($p_{Bonf} < 0.05$).

Discussion

The objective of the study was to investigate the effects of sprint interval exercise combined with continuous hypoxia and inter-effort hypoxia on force and physiological parameters in tethered swimming. The main finding was that the IEH condition showed better performance in tethered swimming compared to the NOR condition but was not superior to the HYP condition.

This superiority and benefits of IEH compared to training in NOR have been evidenced in recent studies, in acute sessions,[13,28] and chronic training.[29] Interestingly, we found higher impulse and less fatigue index with very large effect in the HYP (d = 1.12; d = -1.71, respectively) and IEH (d = 1.03; d = -1.36, respectively) compared to NOR condition. In these conditions, impulse showed variations throughout the session and was higher compared to NOR values. This behavior may indicate that under conditions with lower oxygen concentration, it is possible to maintain higher force levels over time, which is why impulse values were higher and the fatigue index was lower in the hypoxic conditions compared to normoxic. This finding is entirely contrary to what the literature supports, namely that performing efforts under continuous or intermittent hypoxia conditions reduces sprint capacity and affects the technical quality of efforts in other modalities, due to low oxygen availability and decreased reoxygenation capacity.[12,30] On the other hand, when mean force was normalized by peak force, the differences between the HYP and HIE conditions compared to NOR disappear. In the HYP condition, swimmers achieved 38.6% of peak force, with no significant difference compared to the 36.8% achieved in NOR. In contrast, in the IEH condition, swimmers achieved 35.5%, showing lower values and a significant difference compared to the HYP condition. In this scenario, the HYP condition likely favored the maintenance of higher force levels throughout the session and showed a medium effect (d = 0.48). Physiological explanation for hypoxic conditions being greater performance to normoxic condition, is an increased vasodilation potentiated by hypoxia,[31] this may have contributed to improve the aerobic contribution by increasing the supply of energy substrates and oxygen distribution to the system, resulting in the maintenance of anaerobic fitness throughout the session, given that the recovery interval between efforts is considered long (i.e., > 3 minutes). Still, in high-intensity efforts, the sympathetic nervous system acts predominantly and this response can be enhanced in the hypoxic condition.[32] To remain a long recovery interval in HYP condition allow for greater sympathetic activation during the session, which contributes to greater performance in hypoxic conditions compared to normoxic conditions.

Recent studies have shown that there are no differences between the IEH and NOR conditions in physiological variables such as heart rate, blood lactate, and rate of perceived exertion, as well as in training impulse relative to each of these variables.[13] Our findings are consistent with these studies, except for heart rate values and $TRIMP_{HR}$ were higher in 7 to 8 bpm and 6 to 7%, respectively, for IEH with evidence of the difference compared to NOR and HYP, presents a very large effect size. These authors emphasize the importance of monitoring internal training load for planning the training program.[13] That said, it is suggested that the IEH model, despite showing a much higher external load compared to NOR (Δ SpO_2 = -14.51%) and HYP (Δ SpO_2 = -13.01%), presents similar internal load values, meaning that perceived exertion is lower even when performing at high intensities and with a greater external stimulus. The inclusion of continuous hypoxia in the present experiment were expected changes in these variables that might impair session performance. However, it was found that in tethered swimming, $TRIMP_{HR}$ in the HYP condition did not differ from the NOR condition, while in the IEH condition it was higher than NOR and HYP. Given this contradiction, it is suspected that the heart rate modulation in swimming is influenced by hydrostatic pressure,[33] which, in turn, aids in heart rate recovery and the modulation of the entire system during sprint interval exercise, resulting in lower perceived exertion.[28] In the IEH condition, alternating external stimuli may lead to a greater demand on the autonomic system to regulate heart rate, which can result in a higher perception of effort, even when performing efforts at equivalent intensities.

Despite the study's effort to include a condition of complete hypoxia, we faced some limitations that may affect the results. As mentioned earlier, tethered swimming does not reflect the actual context of swimming training, although it shows positive correlations with free swimming performance.[34,35] This could have led to changes in swimming technique and force application during efforts. Lastly, the sample could have been more homogeneous, and although the swimmers had experience in the sport, at a high-performance level, different results might be observed.

In conclusion, the HYP and IEH condition during sprint interval exercise can be considered a model that enhances performance in propulsive force parameters compared to the NOR condition in swimmers. The IEH model does not differ from the hypoxic condition, although there is a greater perception of effort and greater changes in heart rate of this condition. Future studies are needed to investigate whether the sympathetic nervous system is indeed the primary mechanism responsible for contributing to the increase in strength under hypoxic conditions, as well as the rise in heart rate and perceived exertion during IEH conditions. The advantage is that the IEH model ensures the same performance as continuous hypoxia, but with the possibility of performing the efforts in normoxia and with less discomfort due to the possibility of recovering in hypoxia by wearing a mask rather than a snorkel throughout the session. Coaches and athletes can use this training session model associated with hypoxic conditions to optimize performance, with the aim of ensuring a higher quality of effort at a specific moment which requires greater propulsive force production during the session.

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