

Intermittent hypoxic training for 6 weeks in 3000 m hypobaric hypoxia conditions enhances exercise economy and aerobic exercise performance in moderately trained swimmers

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ABSTRACT: Athletic endurance performance at sea level can be improved via intermittent hypoxic training (IHT). However, the efficacy of IHT for enhancement of aerobic exercise performance at sea level is controversial because of methodological differences. Therefore, the aim of the study was to determine whether the IHT regimen ameliorates exercise economy and aerobic exercise performance in moderately trained swimmers. A total of 20 moderately trained swimmers were equally assigned to the control group (n=10) training in normoxic conditions and the IHT group (n=10) training at a simulated altitude of 3000 m. They were evaluated for metabolic parameters and skeletal muscle oxygenation during 30 min submaximal exercise on a bicycle, and aerobic exercise performance before and after 6 weeks of training composed of aerobic continuous exercise set at 80% maximal heart rate (HRmax) during 30 min and anaerobic interval exercise set at the exercise load with 90% HRmax measured in pre-test during 30 min (10 times 2 min exercise and 1 min rest). According to the results, the IHT group demonstrated greater improvement in exercise economy due to decreases in $\dot{V}O_2$ ($p=.016$) and HHb ($p=.002$) and increases in O_2Hb ($p<.001$) and TOI ($p=.006$). VCO_2 was decreased in the IHT group ($p=.010$) and blood lactate level was decreased in the control ($p=.005$) and IHT groups ($p=.001$). All aerobic exercise performance including VO_{2max} ($p=.001$) and the 400 m time trial ($p<.001$) were increased in the IHT group. The present findings indicate that the 6 week IHT regime composed of high-intensity aerobic continuous exercise and anaerobic interval exercise can be considered an effective altitude/hypoxic training method for improvement of exercise economy and aerobic exercise performance in moderately trained swimmers.

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INTRODUCTION

Since the Olympic Games were held at a high altitude in Mexico City in 1968, the usefulness of training at altitude or in hypoxic conditions for the improvement of aerobic exercise performance has received considerable attention among athletes, coaches, and scientists [1]. Aerobic exercise performance is related to various factors that can be altered by diversiform training methods at altitude or in hypoxic conditions including erythropoiesis, exercise economy, capillary density, haemodynamic function, and acid-base response in skeletal muscle [2, 3].

Athletic endurance performance at sea level can be improved via three altitude/hypoxic training methods: the living high-training high (LHTH) (residing and training in natural altitude environments or artificial hypoxic conditions), the living high-training low (LHTL) (residing at natural altitude or in artificial hypoxic conditions, but

training at or near sea level), and the living low-training high (LLTH) (residing at sea level and training at natural altitude or in artificial hypoxic conditions) regime [4, 5, 6].

The LHTH and LHTL regimes have shown efficacy in enhancing aerobic exercise performance and time trials in various athletes, resulting in an increase in maximal oxygen consumption (VO_{2max}) due to positive changes in haematological parameters such as increased red blood cell (RBC) count, RBC mass, haemoglobin (Hb) mass, and erythropoietin (EPO) concentration [6, 7, 8]. However, many researchers have reported that athletes, in order to enhance aerobic exercise performance, must reside and train in 1500-4000 m altitude/hypoxic conditions for 24 hours in the LHTH regime and > 16 hours in the LHTL regime [6, 9, 10]. These training regimes can be performed in countries that have a natural high-altitude

environment, including Ethiopia and Kenya, or have various and expensive simulated altitude equipment such as a hypoxic hotel, training centre, chamber, etc. Many elite athletes have participated in natural altitude training camps in other countries, such as Albuquerque in the United States, Kunming in China, and Chamonix in France [2].

Recently, intermittent hypoxic training (IHT), an LLTH approach, may be of particular interest to athletes and coaches because this training regime commonly involves shorter hypoxic exposure (approximately two to five sessions per week of < 3 hours), lower cost, less effort, and shorter time than the LHTH and LHTL regimes [8]. The stress of hypoxia, in addition to training stress, will compound the training adaptations experienced with normal endurance training and will lead to greater improvements in aerobic exercise performance [11, 31, 32]. IHT may enhance exercise economy, acid-base balance, metabolic, and haemodynamic response during exercise, resulting in improved oxygen utilizing capacity and exercise performance [11-14].

However, the efficacy of aerobic exercise performance in IHT at sea level is still controversial [15, 16, 17, 18]. These conflicting results may be due to methodological difference including the dose of hypoxic stimulus, type and intensity of training, participant training status, and time-point in measurement of aerobic exercise per-

formance following the IHT procedure [13, 32]. McLean *et al.* [8] performed a systemic review that aimed to evaluate the normoxic aerobic exercise performance outcomes of the IHT literature, with a particular focus on training intensity and modality. As the results showed, the improvement in aerobic exercise performance following IHT interventions appeared to be more strongly related to training carried out with the high-intensity and anaerobic interval method. Also, the IHT regime should always include some portion of high-intensity training in normoxic conditions, given that some physiological systems are limited under hypoxic conditions.

Therefore, this study aimed to investigate the effects of a high-intensity IHT regimen (< 3 hours' hypoxic exposure, 3 times per week, 6 weeks) composed of aerobic continuous treadmill and anaerobic interval bicycle exercise, and normoxic training (swimming and resistance exercise) on metabolic parameters, skeletal muscle oxygenation profiles, and aerobic exercise performance in moderately trained swimmers.

MATERIALS AND METHODS

Participants

Our study included 20 moderately trained Korean swimmers who had not participated in any exercise and training programme in hypobaric and normobaric hypoxic conditions in the previous 6 months.

TABLE 1. Participant characteristics.

Variable	Pre	Post
Participant (<i>N</i>)		
Control group		10 (5 male, 5 female)
IHT group		10 (5 male, 5 female)
Training condition (torr)		
Control group		760 (sea-level)
IHT group		526 (simulated 3000 m)
Age (year)		
Control group		22.9 ± 3.9
IHT group		22.5 ± 2.6
Height (cm)		
Control group		175.0 ± 9.9
IHT group		174.6 ± 9.2
Weight (kg)		
Control group	69.2 ± 12.9	68.6 ± 12.9
IHT group	72.7 ± 10.4	72.4 ± 11.0
Body fat (%)		
Control group	20.7 ± 4.0	20.5 ± 3.6
IHT group	22.1 ± 4.3	21.9 ± 3.7

Pre = before training; Post = after training; IHT = intermittent hypoxic training

The participants were non-smokers, and did not have any history of musculoskeletal, cardiovascular, or pulmonary disease. The participants received information about the purpose and process of this study. All swimmers consented by signature, after sufficient explanation of the experiment and understanding of the possible adverse effects prior to the start of the study, and were equally divided according to number ($n=10$) and sex (5 men and 5 women) and randomly assigned to one of the two intervention groups: a control group for normoxic training (760 Torr) and an IHT group for training at a simulated altitude of 3000 m (526 Torr) hypobaric hypoxic conditions. All participants completed the study; thus, all data were used in the analyses. There were no significant differences in physical characteristics between groups (Table 1).

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation and with the Declaration of Helsinki, and this study was approved by the Institutional Review Board of Konkuk University (HR-090) in Korea and was conducted according to the Declaration of Helsinki.

Study design

Our study was conducted as follows: 8 days of pre-test sessions (i.e., all dependent variables were measured at 2-day intervals for a total of 8 days), 6 weeks of training sessions under each environmental condition (i.e., normoxic or 3000 m simulated hypoxic conditions), and finally, 8 days of post-test sessions.

In the test sessions, on the first day, we measured body composition between 8:00 and 9:00 am after 4 hours or more of fasting. After about 2 hours of meals and rest, maximal oxygen consumption (VO_{2max}) and maximal heart rate (HRmax) were measured using graded exercise testing by the Bruce protocol on a treadmill in normoxic conditions. On the second day, all participants underwent measurement of the exercise load (watts) corresponding to 75% and

90% HRmax using graded exercise testing by the McArdle protocol on a bicycle in normoxic and hypoxic conditions. On the third day, metabolic parameters and skeletal muscle oxygenation profiles were measured during 30 min of submaximal exercise on a bicycle in all participants in normoxic conditions. Exercise intensity was set at individual bicycle exercise load values (watts) corresponding to 75% HRmax obtained at pre-test in normoxic conditions. On the fourth day, all swimmers underwent a 400 m time trial in freestyle in an authorized indoor swimming pool (50 m length) at sea level in Seoul.

For aerobic exercise performance, they performed four kinds of training session in each environmental condition (control group – normoxic conditions; IHT group – simulated 3000 m hypoxic conditions) for 90 min: warm-up, aerobic continuous exercise, anaerobic interval exercise, and cool-down. Warm-up and cool-down were set at 50% HRmax for each swimmer for 5 min, then increased by 10% HRmax every 5 min and performed for 15 min. Aerobic continuous exercise on a treadmill was performed at 80% HRmax for 30 min and interval training on a bicycle set at the exercise load with 90% HRmax measured in pre-test for 30 min (10 times 2 min exercise and 1 min rest). These training sessions were conducted in the laboratory and training frequency was 90 min, 3 days per a week, during 6 weeks. The velocity in warm-up, aerobic continuous exercise, and cool-down on a treadmill were changed using a heart rate monitor (Polar S610i, Finland) to match each heart rate. Anaerobic interval exercise intensity was set at individual bicycle exercise load values (watts) with 90% HRmax obtained at pre-test in each environmental condition (control group – normoxic conditions; IHT group – hypoxic conditions).

Also, all participants performed equally additional normoxic training sessions composed of a swimming training session (warm-up, drills, main set, and swim down) and resistance training session (bench press, shoulder press, dumbbell curl, lat pull-down, bent-over

TABLE 2. Swimming exercise for normoxic training in all participants.

Sessions	Exercise program
Warm-up	400 m slow and easy, working on your water feel. Alternating Freestyle and Backstroke, 50 m each.
Drills	4 × 50 Freestyle only leg kick without kickboard breathing frontally, 30 sec rest in between. 4 × 50 breaststroke only leg kick without kickboard breathing frontally, 30 sec rest in between.
Main set	1250 m Pyramid: 50, 100, 150, 200, 250, 200, 150, 100, 50 All Freestyle, medium steady pace, 5-8 slow deep breath rest in between, You can take a longer (3 min) break and have a drink after reaching 250 top level 200 m Backstroke swim down
Swim down	350 m kickboard, 200 deep Freestyle leg kick, 150 long deep breaststroke kick
Total	2.6 km

rowing, bent-over-back, push-up, front push, front raise, and bent-over kickback) at sea level. The swimming training session is shown in Table 2. All participants performed resistance training: 3 sets of 8-10 repetitions at exercise intensity range from 70% to 80% of one-repetition maximum, with 60 seconds rest per set.

We designed a study to evaluate the effectiveness in IHT intervention compared to normoxic training. Therefore, before and after training, we analysed metabolic parameters (minute ventilation, VE; oxygen consumption, VO_2 ; carbon dioxide excretion, VCO_2 ; respiratory exchange rate, RER; and lactate blood level) and skeletal muscle oxygenation (concentrations of oxy[haemoglobin + myoglobin], O_2Hb ; deoxy[haemoglobin + myoglobin], HHb ; and tissue oxygenation index, TOI) for 30 min submaximal bicycle exercise corresponding to 75% HRmax obtained before training. Aerobic exercise performance was evaluated before and after training via VO_{2max} and the 400 m time trial.

Training intervention in each environmental condition (normoxic conditions and 3000 m simulated altitude) in both groups and testing were conducted in the laboratory. The 3000 m (526 mmHg) hypobaric hypoxic condition was simulated by a 6.5 m wide

$\times 7.5$ m long $\times 3$ m high hypobaric hypoxic chamber (Submersible Systems, Huntington Beach, CA). The temperature within the laboratory was maintained at $20 \pm 2^\circ C$ and the humidity was maintained at $60 \pm 2\%$ for all the environmental conditions.

Measurement

All participants fasted for 4 hours or more prior to measurement of body composition (i.e., height, weight, % free fat, and % body fat). They wore lightweight clothing and were asked to remove any metal items. An X-SCAN PLUS (Jawon medical, Korea) was used to measure height and body composition at sea level.

Metabolic parameters were measured over the 30 min duration of the exercise protocol in normoxic condition. VE, VO_2 , VCO_2 , and RER were analysed at every minute during rest and submaximal exercise on a bicycle using the Vmax-229 breath-by-breath auto metabolism analyser (SensorMedics, USA), a bicycle (Monark Exercise AB, Vansbro, Sweden), and breathing valve in the facemask form. The summation values were used as measurement values. Blood lactate level was analysed at rest, 5, 10, 20, and 30 min using the YSI-1500 lactate analyser (YSI Inc., USA), and the five

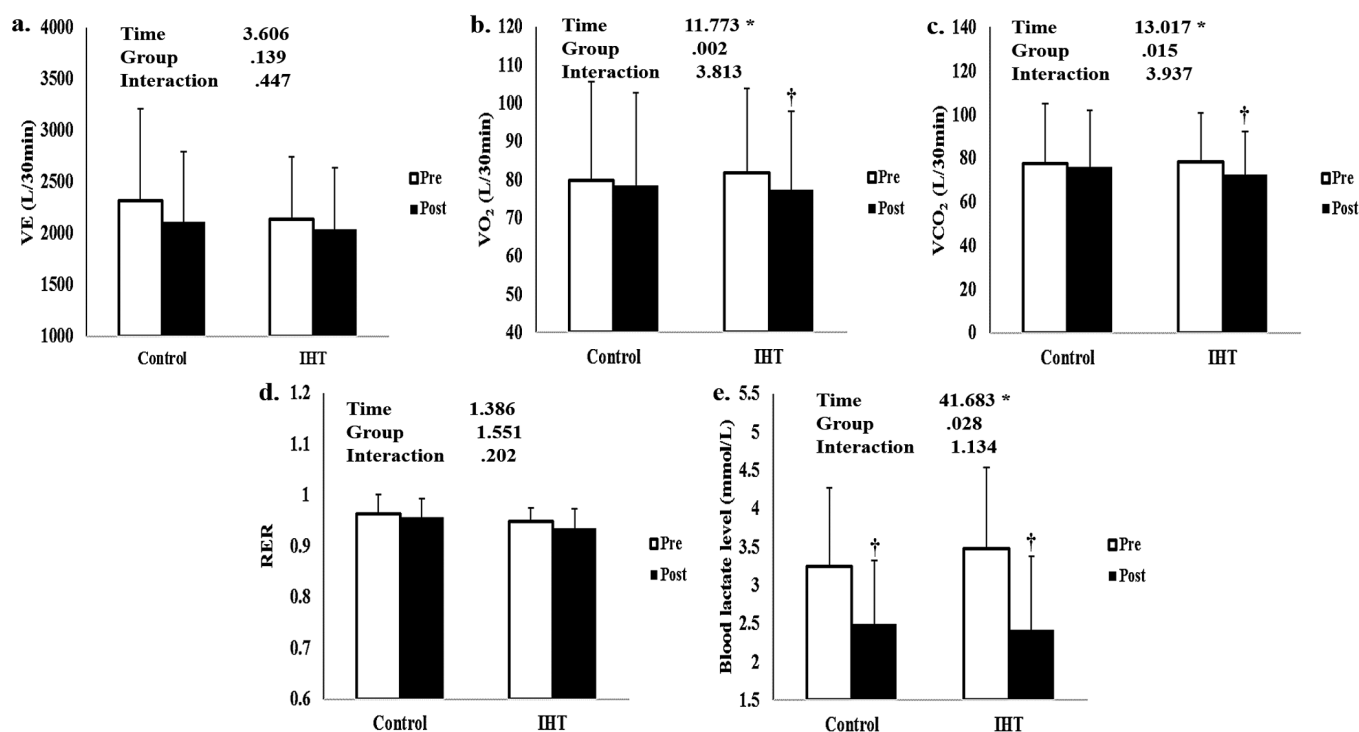


FIGURE 1. Changes in metabolic parameters for 30 min submaximal exercise on a bicycle at Pre and Post by training in control and IHT group.

Note: a = change in minute ventilation (VE), b = change in oxygen consumption (VO_2), c = change in carbon dioxide production (VCO_2), d = change in respiratory exchange ratio (RER), e = change in blood lactate level. The bars indicate the mean \pm S.D. * = significant interaction or main effect, † = significant difference between Pre and Post in each group. Pre = before training; Post = after training; IHT = intermittent hypoxic training.

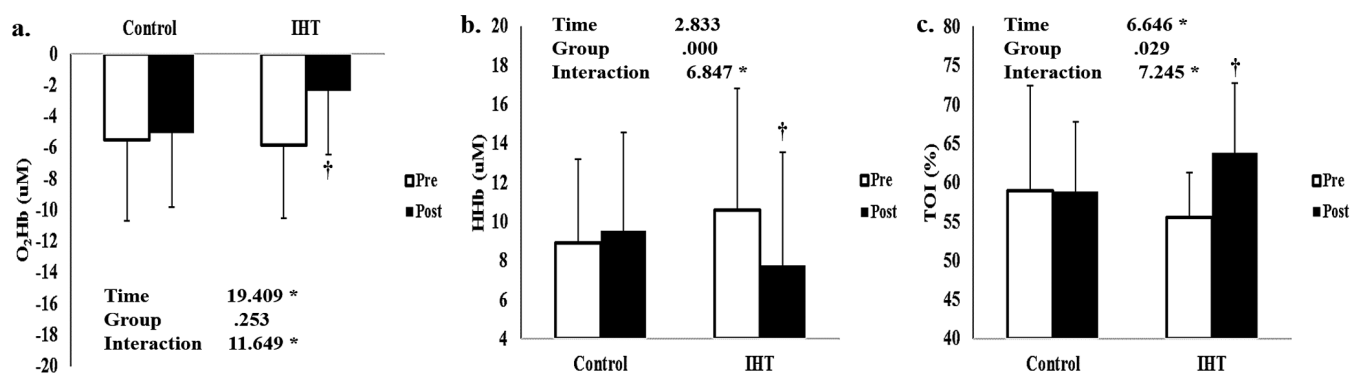


FIGURE 2. Changes in skeletal muscle oxygenation parameters for 30 min submaximal exercise on a bicycle at Pre and Post by training in control and IHT group.

Note: a = change in concentration of oxy-haemoglobin and myoglobin (O_2Hb), b = change in concentration of deoxy-haemoglobin and myoglobin (HHb), c = change in tissue oxygenation index (TOI). The bars indicate the mean \pm S.D. * = significant interaction or main effect, †: significant difference between Pre and Post in each group. Pre = before training; Post = after training; IHT = intermittent hypoxic training.

average values were used as measurement values. For measuring the blood lactate level, we collected 80 μ L of blood in a capillary tube using the fingertip method, and the sample was analysed using the YSI-1500 lactate analyser.

Skeletal muscle oxygenation parameters of the right vastus lateralis were evaluated during rest and 30 min submaximal exercise on a bicycle with a commercially available near infrared spectroscopy (NIRS) system (Hamamatsu NIRO 200, Hamamatsu Photonics, Japan) in normoxic conditions and the average values were used as measurement values. The intensity of incident and transmitted light was recorded continuously and, along with the relevant specific extinction coefficients, used for online estimation of the changes (Δ) from baseline of the concentrations of oxy[haemoglobin + myoglobin] ($[O_2Hb]$), deoxy[haemoglobin + myoglobin] ($[HHb]$), and total [haemoglobin + myoglobin] ($[Hb_{TOT}]$) [20]. From these values, a measurement value of skeletal muscle oxygenation was used for O_2Hb , HHb, and TOI (calculated by $100 \times [O_2Hb]/[Hb_{TOT}]$).

Aerobic exercise performance was evaluated by maximal grade exercise test using a treadmill (Precor 932i, USA) and a 400 m time trial. VO_{2max} was measured before and after training using the Bruce protocol for graded exercise testing on a treadmill (Precor 932i, USA), with a Vmax-229 breath-by-breath auto metabolism analyser (SensorMedics, USA) in normoxic conditions. The 400 m time trial in freestyle was measured twice by an automatic system installed on an authorized indoor swimming pool (50 m) at sea level in Seoul and the median time was used.

Statistical Analyses

Means and standard deviations (SD) were calculated for each primary dependent variable. Normality of distribution of all outcome variables was verified using the Kolmogorov-Smirnov test. A two-way analysis of variance with repeated measures on the “time” factor was

used to analyse the effects of training programmes on each dependent variable. Post-hoc testing using the Bonferroni method was used to identify within-group change over time. An a priori power analysis was performed with G-power for the energy metabolic parameter (VO_2 during submaximal exercise) based on previous research [31], indicating that a sample size of 16 participants (8 participants per group) would be required to provide 80% power at an α -level of .05. We anticipated a more than 10% dropout rate and aimed for a starting population of 20. All analyses were performed using Statistical Package for the Social Sciences (SPSS) version 23.0. A priori, the level of significance was set at .05.

RESULTS

Metabolic parameters measured during 30 min submaximal exercise on a bicycle before and after training are shown in Figure 1. All metabolic parameters showed no significant interaction. However, following training, actual VO_2 ($F=11.773$, $p=.004$), VCO_2 ($F=13.017$, $p=.003$), and blood lactate level ($F=41.683$, $p<.001$) had significant main effects within time; the IHT group showed a significant decrease in VO_2 ($p=.016$), VCO_2 ($p=.010$), and blood lactate level ($p=.001$) between Pre and Post, but the control group showed a significant decrease in blood lactate level ($p=.005$) between Pre and Post. There was no significant interaction or main effect within time in VE and RER.

There was a significant interaction in all skeletal muscle oxygenation parameters of the right vastus lateralis including O_2Hb ($F=11.649$, $p=.004$), HHb ($F=6.847$, $p=.020$), and TOI ($F=7.245$, $p=.018$) during 30 min submaximal exercise on a bicycle (Figure 2). The IHT group showed greater improvement in skeletal muscle oxygenation compared to the control group; O_2Hb ($p<.001$) and TOI ($p=.006$) were increased, and HHb ($p=.002$) was decreased in the IHT group.

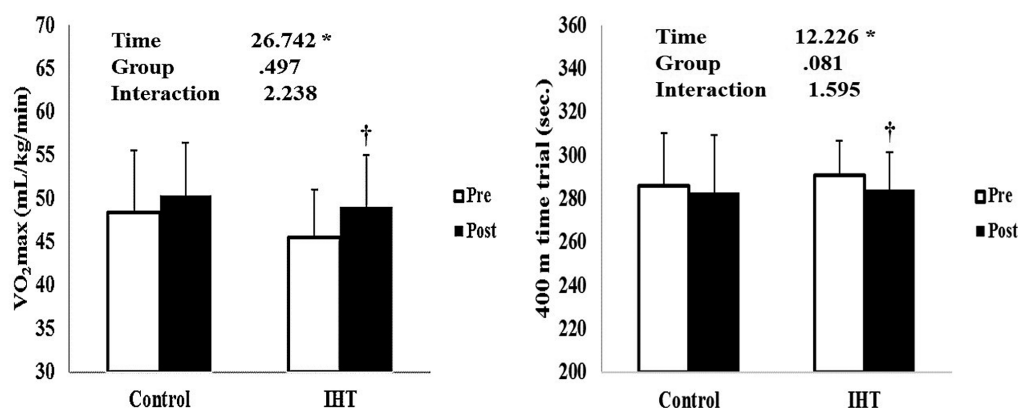


Figure 3. Changes in aerobic exercise performance by training in control and IHT group.

Not: a = change in maximal oxygen consumption (VO₂max), b = change in 400 m time trial. The bars indicate the mean \pm S.D. * = significant interaction or main effect, † = significant difference between Pre and Post in each group. Pre = before training; Post = after training; IHT = intermittent hypoxic training.

There was no significant interaction in exercise performance, but there were significant main effects within time in VO₂max ($F=26.742$, $p<.001$) and the 400 m time trial ($F=12.226$, $p=.004$) (Figure 3). As expected, the IHT group showed improvement in aerobic exercise performance: VO₂max ($p=.001$) and the 400 m time trial result ($p<.001$) were increased in the IHT group.

DISCUSSION

Among altitude/hypoxic training regimes for enhanced aerobic exercise performance in various athletes, IHT commonly involves < 3 hours' hypoxic exposure, two to five times per week, during two to six weeks and, therefore, does not provide a sufficient hypoxic stimulus to induce haematological changes [6, 7, 8]. Therefore, IHT does not induce improvement of aerobic exercise performance via enhancement of oxygen transportation capacity by erythropoiesis such as increased RBC count, RBC mass, Hb mass, and EPO concentration. However, several studies suggest that short-term exposure including some form of physical training (i.e. IHT) has the ability to enhance the metabolic (i.e. blood lactate level, glycolytic enzyme and glucose transport, acid-base regulation) and haemodynamic response and oxygen utilization capacity [11, 12, 13, 14]. However, the efficacy of IHT for the enhancement of aerobic exercise performance at sea level still remains an open question due to methodological differences including the dose of hypoxic stimulus, type and intensity of training, participant training status, and time-point of measurement of aerobic exercise performance following the IHT procedure [15, 16, 17, 18]. Therefore, our study investigated the effectiveness of IHT (< 3 hours' hypoxic exposure, 3 times per week, 6 weeks) and additional normoxic training with respect to metabolic parameters, skeletal muscle oxygenation, and aerobic exercise performance in moderately trained swimmers. The study results

confirmed that the IHT composed of warm-up, aerobic continuous treadmill, anaerobic interval bicycle exercise and cool-down, and additional normoxic training sessions (swimming and resistance exercise) enhanced aerobic exercise performance in moderately trained swimmers by improvement of exercise economy via a tendency to decrease of VO₂, VCO₂, blood lactate level, and Hb, and increase of O₂Hb and TOI, compared to the control group.

Generally, previous studies reported that IHT increases glycolysis enzyme activity, glucose delivery capacity, mitochondria density, capillary density, cross section area of skeletal muscle, and activity of the motor unit by stimulating the neuromuscular system [2, 3, 7, 11]. These positive changes improve the effectiveness of oxygen delivery and utilization capacity [22, 23, 24, 25, 26]. In addition, aerobic exercise performance is enhanced by exercise economy (improvement in inflow rate in oxygen to skeletal muscle tissue and oxygen utilization capacity in mitochondria) [1, 13, 22, 24]. In particular, exercise economy is highly correlated with exercise performance in aerobic athletes [19], and is recognized as an accurate predictive factor in aerobic exercise capacity [21]. Many studies have reported that greater exercise economy is related to increased aerobic exercise performance by the physiological adaptations to altitude/hypoxic training [29, 30]. In our study, the positive changes in VO₂, O₂Hb, Hb, and TOI during submaximal exercise on a bicycle in the IHT group by training are consistent with results of previous studies showing that IHT enhances aerobic exercise performance via improved exercise economy and aerobic energy metabolic rate as oxygen utilization capacity in skeletal muscle tissue [1, 2, 22, 27].

However, a number of previous studies failed to demonstrate an improvement in exercise economy and aerobic exercise performance at sea level [17, 18, 28]. These conflicting results may be due to

methodological difference including the dose of hypoxic stimulus, type and intensity of training, participant training status, and time-point of measurement of aerobic exercise performance following the IHT procedure [13]. Among various methodological differences, exercise mode and intensity are likely key factors in mediating the response to IHT. The higher training intensities appear to be more beneficial than sub-maximal workloads, and the IHT intervention should always include some portion of high-intensity anaerobic and resistance training in normoxia, given that some physiological systems are limited under hypoxic conditions [8]. Moreover, IHT is thought to induce primarily peripheral adaptations related to metabolic parameters and skeletal muscle oxygenation [29, 30]. Previous studies showing negative results may not have been sufficient to stimulate these adaptations and improve exercise economy or aerobic exercise performance [8, 11]. Additionally, McLean et al. [8] suggested that greater aerobic exercise performance with IHT might be more likely if the following criteria are fulfilled: (1) high-intensity intervals are completed during the IHT regimen; (2) sufficient intensity and volume of normoxic training accompanies the IHT. In our study, as McLean et al. [8] suggested, we applied high-intensity aerobic continuous training on a treadmill corresponding to 80% HR_{max} and anaerobic interval training on a bicycle corresponding to 90% HR_{max} (the exercise load with 90% HR_{max} at Pre). In addition, there were sufficient intensity and volume of additional normoxic training (swimming and resistance exercise) carried out with IHT. As a result, our team considers that enhanced exercise economy via IHT increased aerobic exercise performance (VO_{2max} and 400 m time trial) with a tendency to a decrease in VCO₂ and blood lactate level due to an increased aerobic energy metabolic rate and consolidated tolerance and removal capacity to fatigue-causing substances during anaerobic energy metabolism in moderately trained swimmers [1, 2, 22, 24]. From these results, the majority of benefits following the IHT regime appear to be related to aerobic exercise performance, which may be more beneficial in athletes with high intensity of anaerobic interval or repeated exercise in hypoxic conditions and normoxic exercise. In particular, when applying IHT to athletes for exercise performance,

sufficient high intensity and volume of normoxic training, such as interval exercise, repeated sprint exercise, and resistance exercise, may be advised. Also, athletes, coaches, and scientists should carefully apply the principles of training specificity. Therefore, the IHT in the present study can be considered an effective altitude/hypoxic training regime for improvement of exercise economy and aerobic exercise performance in moderately trained swimmers.

CONCLUSIONS

Our results suggest that 6 weeks of IHT (< 3 hours' hypoxic exposure, 3 times per week, 6 weeks) composed of warm-up, aerobic continuous training, anaerobic interval training, and cool-down in simulated 3000 m hypoxic conditions, and additional normoxic training (swimming and resistance exercise), is effective in enhancing exercise economy. In addition, we provide findings regarding greater improved tendency in removal capacity of fatigue substances and aerobic exercise performance of moderately trained swimmers.

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