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The performance and aerobic endurance effects of high-intensity versus moderate-intensity continuous running

Even Jarstad and Asgeir Mamen

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Abstract: The aim of the present study was to investigate the performance and aerobic endurance effects of high-intensity (HICR) versus moderate-intensity continuous running (MICR), which were nonmatched for total work. Twenty healthy recreational athletes (aged 28 ± 5 years) were randomly assigned to an HICR, MICR, or no-intervention control (C) group. The HICR group ($n = 7$) performed a 20-min strenuous, almost exhausting, run above lactate threshold (LT) at ~88% of maximal heart rate (HR_{max}), whereas the MICR group ($n = 7$) performed a 40-min run at ~80% HR_{max}. Both the HICR and MICR groups performed 3 intervention sessions a week, in addition to ~60% of their regular aerobic exercise, for 10 weeks. The C group ($n = 6$) performed regular physical exercise throughout the study. Time to exhaustion, during a ~4–8-min ramp test procedure, was significantly increased by 23% and 24% ($P < 0.01$) following HICR or MICR, respectively, with no significant difference in the change in time to exhaustion ($P = 1.00$) at pre- to post-training between the 2 training modalities (HICR and MICR). In the HICR group, maximal oxygen consumption and velocity at LT increased significantly by 5.0% and 6.8% ($P < 0.01$), respectively. The MICR group increased relative maximal oxygen consumption (mL·kg^{-1}·min^{-1}) significantly by 4.7% ($P < 0.05$), whereas the pulmonary respiratory gas-exchange ratio was significantly decreased at a submaximal workload by 4.2% ($P < 0.01$), indicating enhanced fat oxidation. No performance or physiological effects were observed in the C group. The present study indicates that even with a substantially lower total energy turnover, HICR can be as performance enhancing as MICR. Moreover, HICR can increase maximal aerobic power, whereas MICR may enhance fat oxidation.

Key words: recreational athletes, time to exhaustion, maximal oxygen consumption, lactate threshold, running economy, substrate oxidation.

Résumé : Le but de la présente étude est d'examiner les effets sur la performance et l'endurance aérobie de la course continue d'intensité élevée (« HICR ») par rapport à la course continue d'intensité modérée (« MICR »), ces courses n'étant pas appariées en fonction du travail total. Vingt athlètes par loisir, en bonne santé (âgés de 28 ± 5 ans) sont répartis au hasard dans les groupes HICR, MICR ou de contrôle sans intervention (« C »). Le groupe HICR ($n = 7$) effectue durant 20 min une course intense, presque épuisante, au-dessus du seuil de lactate (« LT ») à ~88 % de la fréquence cardiaque maximale (« HR_{max} »); le groupe MICR ($n = 7$) effectue durant 40 min une course à ~80 % HR_{max}. Les groupes HICR et MICR effectuent pendant 10 semaines trois séances d'intervention par semaine, en plus de ~60 % de leurs exercices aérobiques réguliers. Le groupe C ($n = 6$) fait régulièrement de l'exercice physique tout au long de l'étude. Le temps jusqu'à l'épuisement durant les ~4–8 min d'un protocole de test par incrément s'accroit de 23 % et 24 % ($P < 0,01$) après IRCH ou MICR, sans différence significative pré-post-entraînement du temps jusqu'à l'épuisement ($P = 1,00$) entre les deux modalités d'entraînement (HICR et MICR). Dans le groupe HICR, la consommation maximale d'oxygène et la vitesse à LT augmentent significativement de 5,0 % et 6,8 % ($P < 0,01$) respectivement. Le groupe MICR accroit significativement son consommation maximale d'oxygène relatif (mL·kg^{-1}·min^{-1}) de 4,7 % ($P < 0,05$), tandis que le ratio d'échanges gazeux diminue significativement de 4,2 % ($P < 0,01$) à une intensité de travail sous-maximale, indiquant ainsi un accroissement de l'oxydation des graisses. On observe dans le groupe C aucun effet physiologique ou sur la performance. La présente étude indique que, même avec une beaucoup plus petite transformation d'énergie totale, HICR peut aussi bien accroître la performance que MICR. De plus, HICR peut augmenter la puissance aérobie maximale, alors que MICR peut augmenter l'oxydation des graisses. [Traduit par la Rédaction]

Mots-clés : athlètes par loisir, temps d'épuisement, consommation maximale d'oxygène, seuil de lactate, économie de la course, oxydation du substrat.

Introduction

The performance and physiological effects of aerobic running exercise are relatively well documented in recreational athletes (Thomas et al. 1984; Olsen et al. 1988; Franch et al. 1998; Esfarjani and Laursen 2007; Helgerud et al. 2007; Macpherson et al. 2011; Rowan et al. 2012; Sandvei et al. 2012; Ulloa et al. 2015). However, while several studies have examined the training effects of moderate-intensity continuous running (MICR; 60%–80% of max-

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E. Jarstad. Norwegian School of Sport Sciences, Department of Physical Performance, PO Box 4014 Ullevaal stadion, 0806 Oslo, Norway; Norwegian Sport Medicine Clinic (Nimi), Department of Cardiology and Exercise Physiology, PO Box 3843 Ullevaal stadion, 0805 Oslo, Norway.
A. Mamen. Kristiania University College, School of Health Sciences, Ernst G Mortensens stiftelse, PO Box 1190 Sentrum, 0107 Oslo, Norway.
Corresponding author: Even Jarstad (email: evenjarstad@gmail.com).

imal oxygen consumption ($\dot{V}O_{2max}$)/70%–85% of maximal heart rate (HR_{max})) (Thomas et al. 1984; Helgerud et al. 2007; Macpherson et al. 2011; Rowan et al. 2012; Sandvei et al. 2012; Ulloa et al. 2015) and high-intensity interval running (HIIR; >80% $\dot{V}O_{2max}$/>85% HR_{max}) (Thomas et al. 1984; Olsen et al. 1988; Franch et al. 1998; Esfarjani and Laursen 2007; Helgerud et al. 2007; Ulloa et al. 2015), it appears that only 1 study has investigated the performance and physiological effects of high-intensity continuous running (HICR; >80% $\dot{V}O_{2max}$/>85% HR_{max}) (Franch et al. 1998). In that particular study, Franch et al. (1998) reported that 6 weeks of HICR (20–30 min, 3 times a week, ~93% HR_{max}) improved running performance more than, and aerobic endurance similarly to, HIIR (4–6 times 4 min/2-min pauses, 3 times a week, ~94% HR_{max}) in recreational runners. This indicates that HICR may be an underestimated training modality. Therefore, it is of great interest to provide further scientific evidence of the training effects of HICR.

To the best of our knowledge, HICR has not been compared with lower-intensity running exercise of longer duration. The aim of the present study was, therefore, to investigate the performance and aerobic endurance effects of HICR versus MICR in recreational athletes. We chose a practical approach to the issue by not matching the 2 training modalities (HICR and MICR) for total work.

Materials and methods

Subjects

Twenty-seven subjects, who participated regularly in aerobic exercise for 2 to 3 times a week, were enrolled for the present study. The subjects were randomly assigned to an HICR, MICR, or no-intervention control (C) group. Three participants dropped out during the study because of lack of time, injury, or personal conflicts, whereas 4 subjects were excluded from analysis because of too few intervention sessions, illness, or participation in another study. Ultimately, 20 subjects (7 women and 13 men), aged 28 ± 5 years, completed the present study. Compared with a predominantly Caucasian population (Edvardsen et al. 2013), the pretraining relative $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}) in these 7 women (age: 20–29 years, n = 5, 114% ± 12% of mean values; and age: 30–39 years, n = 2, 114% ± 11% of mean values) and 13 men (age: 20–29 years, n = 8, 113% ± 9% of mean values; and age: 30–39 years, n = 5, 122% ± 8% of mean values) were above mean values for each sex and age group. Among the HICR (n = 7; 3 women, 4 men), MICR (n = 7; 3 women, 4 men), and C groups (n = 6; 1 woman, 5 men), there were no significant differences in allometrically scaled relative $\dot{V}O_{2max}$ (mL·kg$^{-0.75}$·min^{-1}) pretraining. Allometric scaling of relative $\dot{V}O_{2max}$ (mL·kg$^{-0.75}$·min^{-1}, or alternatively mL·kg$^{-0.67}$·min^{-1}) and oxygen consumption ($\dot{V}O_2$) submaximally takes into account individual differences in body mass, for instance between varying performance levels (Ingjer 1991*b*) and sex (Bergh et al. 1991), and may, therefore, be more appropriate than the conventional unit mL·kg^{-1}·min^{-1} when comparing aerobic fitness between different groups pooled for women and men.

Before the study commenced, the subjects gave written informed consent and the project was approved by the South-Eastern Norway Regional Committee for Medical and Health Research Ethics.

Exercise test procedures

Prior to the study, all the subjects performed a complete initial habituation test procedure; the pre- and post-test were then conducted within 10 weeks. The same technician conducted the pre- and post-tests at approximately the same time of the day, in about the same climatic conditions (temperature and relative humidity) in the laboratory. To avoid communication problems and disturbances in the interaction between the technician and participants during testing, the participants were not allowed to listen to music or have any spectators in the laboratory. All tests started with measurement of body mass, followed by 2 treadmill protocols to determine running performance and aerobic endurance.

For determination of running economy, substrate oxidation, and lactate threshold (LT), a stepwise test protocol was used. The stepwise test protocol started with an initial 10-min workload that corresponded to 55% ± 4% of the individual pretraining $\dot{V}O_{2max}$, after which the velocity was increased by 1.0 km·h^{-1} each fifth minute, for 4 to 6 workloads (modified from Borch et al. (1993)). The inclination was constant during the test and set to either 1.7% (1°) or 5.3% (3°) according to individual preferences. $\dot{V}O_2$, heart rate (HR), and pulmonary respiratory gas-exchange ratio (RER) were recorded in steady-state phase, between the third and fifth minutes at each workload (Helgerud et al. 1990; Barstow 1994), whereas blood lactate concentration (BLC) was measured during a standardized 60-s break between the workloads (modified from Helgerud et al. (1990)). The individual velocity corresponding to ~70% pretraining $\dot{V}O_{2max}$ was used to indicate running economy (Støren et al. 2008), whereas RER at 3 individual, submaximal workloads up to ~75%–80% pretraining $\dot{V}O_{2max}$ was used to calculate substrate oxidation (Jeukendrup and Wallis 2005). For determination of the individual LT, the following equation was used: individual BLC during warm-up + 1.5 mmol·L^{-1}, which has been shown to be a satisfactory approach to the "gold standard", maximal lactate steady-state (Helgerud et al. 1990).

After 10 min of active rest, an exhausting ramp test protocol was used to measure $\dot{V}O_{2max}$ and time to exhaustion. The constant inclination during the ramp test was set to 5.3% (3°), and the test started with an initial velocity, which corresponded to 91% ± 9% of the individual pretraining $\dot{V}O_{2max}$. The running speed was then increased each minute by 1.0 km·h^{-1} to a supramaximal workload (124% ± 6% of the individual pretraining $\dot{V}O_{2max}$) and volitional exhaustion within 4–8 min (modified from Tønnessen et al. (2014) and Ingjer (1992)). $\dot{V}O_{2max}$ was defined as the mean of the 2 highest consecutive 30-s $\dot{V}O_2$ measurements (Sandvei et al. 2012; Tønnessen et al. 2014). The main criterion for attainment of $\dot{V}O_{2max}$ was a levelling off of $\dot{V}O_2$, despite increased workload (Taylor et al. 1955). If a levelling off of $\dot{V}O_2$ was not present, at least 2 of the following 3 additional criteria had to be achieved: an RER ≥ 1.10 (Franch et al. 1998; Sandvei et al. 2012), BLC ≥ 6 mmol·L^{-1} at 2 min after completed test (Sandvei et al. 2012), and visible exhaustion of the subject (Esfarjani and Laursen 2007). Retest was carried out if the criteria were not met. For estimation of velocity at $\dot{V}O_{2max}$ ($v\dot{V}O_{2max}$), a mathematical regression line was drawn through 3 to 4 $\dot{V}O_2$ values below LT (steady-state $\dot{V}O_2$ values from the stepwise test procedure), and then extrapolated to the individual $\dot{V}O_{2max}$ recorded (modified from Franch et al. (1998)). As time to exhaustion was used as a measure of running performance, each subject performed identical workloads (inclination and velocities) during the ramp test at pre- and post-training. The participants were not able to view the time on the running clock during the ramp test, and were not informed about their time to exhaustion until the project was finished. In accordance with Ingjer (1991*a*), HR_{max} was calculated as peak HR (HR_{peak}) + 5 beats·min^{-1}; this differs from Franch et al. (1998) and others (e.g., Helgerud et al. 2007; Sandvei et al. 2012), who seem to have used HR_{peak} as HR_{max}. Therefore, to make this study comparable to others, we also indicated the exercise intensities in percentage of both HR_{peak} and $\dot{V}O_{2max}$ in the HICR and MICR groups.

Instruments

All tests were carried out on a treadmill (Woodway ELG 2; Woodway GmbH, Weil am Rhein, Germany). $\dot{V}O_2$, carbon dioxide production, RER, and ventilation were measured with an Oxycon Champion with mixing chamber (Vyaire Medical, Höchberg, Germany). During the exercise tests, the participants breathed through a rubber mouthpiece connected to a 2-way non-rebreathing valve (2700 series; Hans Rudolph Inc., Kans., USA), and wore a nose clip to avoid nasal breathing. The expired air was led through an ~2-m long tube into the mixing chamber for subsequent analyses of oxygen (O_2), carbon dioxide (CO_2), and ventilation. As far as the authors know, no scientific studies have validated the Oxycon Champion against the "gold standard", the Douglas bag method. However, the successor to Oxycon Champion, the Oxycon Pro, which relies on the same gas (O_2 and CO_2) and ventilation measurement principles as the Oxycon Champion (service manuals for Oxycon Champion and Pro (Vyaire Medical, Höchberg, Germany)), has been shown to be an accurate and reliable system for gas (O_2, CO_2, and thus RER) and ventilation measures over a wide range of ventilations (~15–210 L·min^{-1}), when compared with the Douglas bag method (Foss and Hallén 2005). Furthermore, unpublished data has shown that the Oxycon Champion and Pro are approximately equilibrated for ventilation measurements over a relatively wide range of ventilations (~40–185 L·min^{-1}) (personal communication, Svein Leirstein, physiology laboratory engineer at the Norwegian School of Sport Sciences (NIH 2018)).

Before exercise testing, Oxycon Champion was calibrated against room air and calibration gases with known content (5% CO_2 and 95% nitrogen), whereas volume calibration was conducted manually with a 3-L syringe. BLC of haemolysed blood was measured with a YSI 1500 Sport Analyzer (YSI Inc., Ohio, USA). HR was measured by an HR monitor (Polar Electro Oy, Kempele, Finland) and time measurements were carried out using a digital stopwatch (Hanhart Prisma 200; Hanhart, Germany).

Training intervention

According to individual preferences, the training intervention sessions were carried out on a motor-driven treadmill and/or outdoors. For physiological feedback, all the participants used an HR monitor (Polar Electro Oy) during every intervention session. After a 10-min warm-up, the HICR group performed a 20-min strenuous, almost exhausting, run above LT at ~83% $\dot{V}O_{2max}$ (~88% HR_{max}/~91% HR_{peak}), whereas the MICR group performed a 40-min run at ~72% $\dot{V}O_{2max}$ (~80% HR_{max}/~82% HR_{peak}). The intervention sessions were completed with a 10-min jog corresponding to 60%–70% HR_{max}. Exercise duration in the HICR and MICR groups was chosen based on feasibility and to enable the MICR group to achieve a substantially higher energy expenditure than the HICR group. Calculation of the aerobic energy turnover, i.e., approximately 20 kJ·L $\dot{V}O_2^{-1}$·min^{-1} (Åstrand et al. 2003, p. 238), indicated that the HICR and MICR groups converted ~1320 and ~2230 kJ per session, respectively, excluding warm-up and recovery.

The HICR and MICR groups were set to perform 3 training intervention sessions a week and had to complete at least 80% of the intervention sessions within 10 weeks. In accordance with Franch et al. (1998), both training groups also had to maintain at least ~60% of their habitual aerobic exercise during the study. This was considered appropriate for a satisfactory assessment of training effects among initially trained subjects. All participants in the 2 training groups kept a diary log of exercise duration, training intensity, and type of exercise during the intervention and habitual aerobic training sessions. The training diary showed that the HICR group performed 2.6 ± 0.2 and 1.8 ± 0.6 intervention and regular aerobic exercise sessions a week, respectively. In the MICR group, the equivalent figures were 2.5 ± 0.1 and 1.9 ± 0.9. There were no significant differences between the HICR or MICR groups in the number of training intervention or regular aerobic exercise sessions completed during the study.

Statistical analysis

Results are presented as means ± SD. The significance level was 0.05. Differences between groups at pretraining, and within groups at pre- to post-training, were analysed by a 2-way repeated-measures ANOVA, whereas differences in the changes pre- to post-training between groups were analysed by the 1-way ANOVA, Holm–Sidak method (SigmaPlot 14, Systat Software Inc., San Jose, Calif., USA). Additionally, the effect sizes in the 2 training groups (HICR and MICR) versus the C group were calculated (corrected for bias) in cases where changes in the dependent variables might have been of practical significance, although not being statistically significant. This was conducted on a downloaded Excel spreadsheet (Centre for Evaluation and Monitoring, Durham University, UK (www.cem.org/effect-size-calculator)). The confidence interval was 95%, and an effect size of minimum 0.50 was considered as acceptable; 2 of the 6 effect size categories suggested by Sawilowsky (2009), "medium" (0.50–0.79) and "large" (0.80–1.19), were, therefore, relevant in the present study.

Table 1. Anthropometric variables of the training and control groups at pre- and post-training.

Variable	Pretraining	Post-training
HICR (*n* = 7; 3 women, 4 men)		
Body mass (kg)	78.4±11.0	77.9±11.6
BMI (kg·m^{-2})	23.9±2.3	23.8±2.5
MICR (*n* = 7; 3 women, 4 men)		
Body mass (kg)	76.3±10.4	75.2±10.3*
BMI (kg·m^{-2})	24.0±2.7	23.7±2.6*
C (*n* = 6; 1 woman, 5 men)		
Body mass (kg)	74.2±8.8	73.3±8.3
BMI (kg·m^{-2})	23.3±2.1	23.0±2.1

Note: Data are presented as means ± SD. BMI, body mass index; C, control; HICR, high-intensity continuous running; MICR, moderate-intensity continuous running.
*Significant differences (P < 0.05) within groups at pre- to post-training.

Results

Anthropometry

Body mass and body mass index decreased significantly by 1.4% and 1.3%, respectively, in the MICR group, while no such changes were observed in the HICR or C groups (Table 1).

Performance

Time to exhaustion, during the ~4–8-min ramp test procedure, increased significantly by 23% and 24% in the HICR and MICR groups, respectively, whereas no such change was found in the C group (Table 2).

$\dot{V}O_{2max}$

The HICR group increased $\dot{V}O_{2max}$ significantly, expressed both in absolute (L·min^{-1}: 5.0%) and relative values (mL·kg^{-1}·min^{-1}: 5.7%, mL·kg$^{-0.75}$·min^{-1}: 5.6%) (Table 2). In addition, the HICR group increased $v\dot{V}O_{2max}$ numerically, but not statistically significantly, by 13%, with a medium effect size corresponding to 0.50 (−0.6 to +1.6) (Table 2).

In the MICR group, absolute $\dot{V}O_{2max}$ (L·min^{-1}) increased numerically, but not statistically significantly, by 2.8% (P = 0.09), with a medium effect size of 0.57 (−0.5 to +1.7) (Table 2). Furthermore, a significant increase of relative $\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1}: 4.7%, mL·kg$^{-0.75}$·min^{-1}: 3.8%) was observed in the MICR group (Table 2).

No $\dot{V}O_{2max}$-related changes were found in the C group (Table 2).

LT

The HICR group increased velocity at lactate threshold significantly by 6.8%, while no such effect was observed in the MICR or C groups (Table 2).

Running economy

In the HICR group, the energy cost of running decreased numerically, but not statistically significantly, by 4.2%, with a medium effect size corresponding to −0.54 (−1.7 to +0.6) (Table 2). The energy cost of running increased numerically, but not statistically significantly, by 3.2%, with a large effect size of 1.19 (0.0 to +2.4), in the MICR group (Table 2).

Table 2. Running performance and physiological variables of the training and control groups at pre- and post-training.

Variables	HICR (n = 7; 3 women, 4 men)		MICR (n = 7; 3 women, 4 men)		C (n = 6; 1 woman, 5 men)	
	Pretraining	Post-training	Pretraining	Post-training	Pretraining	Post-training
Performance						
Time to exhaustion (s)	308±36	378±55**	306±53	379±100**	349±59	351±75
$\dot{V}O_{2max}$						
$L \cdot min^{-1}$	3.99±0.77	4.19±0.85**	3.91±0.78	4.02±0.81	4.05±0.83	4.08±0.78
$mL \cdot kg^{-1} \cdot min^{-1}$	50.6±5.4	53.5±6.9**	50.9±7.1	53.3±7.2*	54.5±7.3	55.7±8.1
$mL \cdot kg^{-0.75} \cdot min^{-1}$	150.5±18.5	158.9±22.3**	150.9±22.1	156.7±22.6*	159.7±23.4	162.5±24.3
$v\dot{V}O_{2max}$ ($km \cdot h^{-1}$)	13.6±2.3	15.3±2.8	14.7±2.2	14.4±1.4	14.9±1.4	15.5±3.3
HR_{max} ($s \cdot min^{-1}$)	197±6	193±8	201±11	202±12	195±4	195±5
BLC ($mmol \cdot L^{-1}$)	8.3±1.2	8.1±0.8	8.5±1.3	7.6±1.2	8.6±1.5	8.3±1.2
RER ($\dot{V}CO_2/\dot{V}O_2$)	1.16±0.04	1.14±0.06	1.20±0.05	1.15±0.09	1.20±0.07	1.18±0.08
$\dot{V}_E$ ($L \cdot min^{-1}$)	144±26	146±28	149±33	147±28	149±29	145±28
LT						
vLT ($km \cdot h^{-1}$)	10.3±1.4	11.0±1.4**	11.1±0.9	11.4±1.2	10.6±0.9	10.8±1.1
$\%\dot{V}O_{2max}$	81±3	79±3	80±4	81±3	77±4	79±3
$\%HR_{max}$	86±3	87±2	86±2	87±2	85±2	85±3
BLC ($mmol \cdot L^{-1}$)	2.3±0.2	2.2±0.1	2.1±0.2	2.1±0.1	2.4±0.2	2.3±0.3
Running economy[a]						
Velocity ($km \cdot h^{-1}$)	8.9±1.2	8.9±1.2	9.6±0.8	9.6±0.8	9.3±0.8	9.3±0.8
$\dot{V}O_2$ ($mL \cdot kg^{-0.75} \cdot m^{-1}$)	0.721±0.064	0.694±0.064	0.664±0.054	0.685±0.058	0.713±0.083	0.711±0.093
HR ($s \cdot min^{-1}$)	156±12	148±8	157±5	156±6	151±7	152±11

Note: Data are presented as means ± SD. BLC, blood lactate concentration; C, control; HICR, high-intensity continuous running; HR, heart rate; HR_{max}, maximal heart rate; LT, lactate threshold; MICR, moderate-intensity continuous running; RER, pulmonary respiratory gas-exchange ratio; $\dot{V}CO_2$, carbon dioxide production; $\dot{V}_E$, volume expiration; vLT, velocity at lactate threshold; $\dot{V}O_2$, oxygen consumption; $\dot{V}O_{2max}$, maximal oxygen consumption; $v\dot{V}O_{2max}$, velocity at $\dot{V}O_{2max}$. Significant differences within groups at pre- to post-training (*, $P < 0.05$; **, $P < 0.01$).

[a]Running economy is the energy cost at the velocity corresponding to ~70% pretraining $\dot{V}O_{2max}$.

Table 3. Supplementary physiological variables below LT of the training and control groups at pre- and post-training.

Variables	HICR (n = 7; 3 women, 4 men)		MICR (n = 7; 3 women, 4 men)		C (n = 6; 1 woman, 5 men)	
	Pretraining	Post-training	Pretraining	Post-training	Pretraining	Post-training
Workload I						
Velocity ($km \cdot h^{-1}$)	7.9±1.2	7.9±1.2	8.6±0.8	8.6±0.8	8.3±0.8	8.3±0.8
RER ($\dot{V}CO_2/\dot{V}O_2$)	0.90±0.05	0.92±0.04	0.91±0.03	0.89±0.04	0.93±0.04	0.93±0.03
$\dot{V}O_2$ ($L \cdot min^{-1}$)	2.53±0.51	2.45±0.56	2.51±0.49	2.52±0.48	2.57±0.54	2.52±0.54
$\dot{V}_E/\dot{V}O_2$	24±2	25±2	26±4	26±3	27±5	27±3
$\%\dot{V}O_{2max}$	64±4	59±6**	65±2	63±2	63±2	62±4
BLC ($mmol \cdot L^{-1}$)	1.0±0.1	0.8±0.1**	0.8±0.1	0.7±0.1	1.1±0.2	1.0±0.4
Workload II						
Velocity ($km \cdot h^{-1}$)	8.9±1.2	8.9±1.2	9.6±0.8	9.6±0.8	9.3±0.8	9.3±0.8
RER ($\dot{V}CO_2/\dot{V}O_2$)	0.91±0.05	0.92±0.04	0.92±0.04	0.89±0.03	0.93±0.03	0.93±0.04
$\dot{V}O_2$ ($L \cdot min^{-1}$)	2.79±0.49	2.69±0.58	2.75±0.50	2.80±0.53	2.81±0.56	2.79±0.60
$\dot{V}_E/\dot{V}O_2$	25±2	25±3	27±4	26±3	27±5	28±4
$\%\dot{V}O_{2max}$	70±3	64±7**	71±3	70±2	69±2	68±5
BLC ($mmol \cdot L^{-1}$)	1.3±0.3	1.0±0.2*	1.1±0.2	0.9±0.2	1.5±0.3	1.3±0.5
Workload III						
Velocity ($km \cdot h^{-1}$)	9.9±1.2	9.9±1.2	10.6±0.8	10.6±0.8	10.3±0.8	10.3±0.8
RER ($\dot{V}CO_2/\dot{V}O_2$)	0.94±0.04	0.92±0.04	0.95±0.03	0.91±0.03**	0.96±0.03	0.95±0.03
$\dot{V}O_2$ ($L \cdot min^{-1}$)	3.10±0.52	3.00±0.59	3.00±0.53	3.02±0.52	3.07±0.61	3.09±0.59
$\dot{V}_E/\dot{V}O_2$	27±2	25±3	28±4	27±4	29±5	28±5
$\%\dot{V}O_{2max}$	78±4	72±6**,†	78±3	76±3	76±3	76±3
BLC ($mmol \cdot L^{-1}$)	1.8±0.3	1.3±0.3**	1.6±0.4	1.4±0.4	2.1±0.4	1.9±0.6

Note: Data are presented as means ± SD. BLC, blood lactate concentration; C, control; HICR, high-intensity continuous running; MICR, moderate-intensity continuous running; RER, pulmonary respiratory gas-exchange ratio; $\dot{V}CO_2$, carbon dioxide production; $\dot{V}_E/\dot{V}O_2$, ventilatory equivalent for oxygen; $\dot{V}O_2$, oxygen consumption. Significant differences within groups at pre- to post-training (*, $P < 0.05$; **, $P < 0.01$). Significant differences in the changes between the HICR and C groups at pre- to post-training (†, $P < 0.05$).

Supplementary physiological variables below LT

The HICR group decreased BLC significantly at workloads I, II, and III by 20%, 23%, and 28%, respectively (Table 3). Moreover, significant declines of $\%\dot{V}O_{2max}$ at workloads I, II, and III, corresponding to 7.8%, 8.6%, and 7.7%, respectively, were observed in the HICR group (Table 3). No such changes were observed in the MICR or C groups (Table 3).

In the MICR group, RER decreased numerically, but not statistically significantly, by 2.2% and 3.3% at workloads I and II, respectively, with a medium effect size corresponding to −0.52 (–1.6 to +0.6) and a large effect size of −0.80 (–1.9 to +0.3), respectively (Table 3). Furthermore, RER was significantly decreased by 4.2% at workload III in the MICR group (Table 3), whereas no such effects were observed in the HICR or C groups (Table 3).

Differences in changes pre- to post-training between groups

The significant increase in time to exhaustion in the HICR and MICR groups was numerically, but not statistically significantly, greater than the change in time to exhaustion in the C group (HICR vs C: $P = 0.09$, MICR vs C: $P = 0.08$) pre- to post-training (Table 2). Furthermore, there was no significant difference in the change in time to exhaustion pre- to post-training between the HICR and MICR groups ($P = 1.00$) (Table 2). The only significant inter-group difference in changes pre- to post-training was the decreased $\%\dot{V}O_{2max}$ at workload III observed in the HICR versus C group (Table 3).

Discussion

The main finding in the present study was that HICR increased time to exhaustion similarly to MICR, nonmatched for total work. Other notable findings were that HICR increased absolute $\dot{V}O_{2max}$ and generated a tendency towards enhanced running economy, whereas MICR increased relative $\dot{V}O_{2max}$ and seems to have enhanced fat oxidation. These overall findings indicate that HICR and MICR can produce similar performance improvements, despite various physiological alterations.

HICR

The performance (time to exhaustion) and maximal ($\dot{V}O_{2max}$ and $v\dot{V}O_{2max}$) and submaximal effects (running economy, and BLC and $\%\dot{V}O_{2max}$ at 3 submaximal velocities) in the HICR group of the present study support the results in the HICR group in the study by Franch et al. (1998). Moreover, the performance and aerobic endurance improvements in the HICR group are also in accordance with training effects reported following HIIR in recreational athletes (Thomas et al. 1984; Olsen et al. 1988; Franch et al. 1998; Esfarjani and Laursen 2007; Helgerud et al. 2007). However, no changes of RER were found following HICR, indicating no alteration in fat oxidation. This differs from the finding of Ulloa et al. (2015), who reported significantly increased maximal fat oxidation rate in recreational runners following 8 weeks of HIIR (5–6 times 1 km/3-min pauses, 3 times a week) performed at similar exercise intensity (~83% $\dot{V}O_{2max}$) as that used in the HICR group of the present study. These discrepant findings observed in the present study versus that of Ulloa et al. can be explained by the use of indirect calorimetry and its limitations, as well as the use of different equations for calculating substrate oxidation (Jeukendrup and Wallis 2005). It can also be speculated whether the participants in the HICR group of the present study had already adapted their fat metabolism system through their regular running exercise activities prior to the study. On the other hand, the MICR group, which had similar aerobic fitness pretraining to the HICR group in the present study, appeared to have increased fat oxidation (decreased RER). Therefore, further investigations may be necessary to produce more scientific evidence about the fat oxidation effects of HICR versus MICR in recreational athletes.

MICR

The improvement of performance and/or relative $\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) in the MICR group of the present study supports findings following MICR in previous studies of recreational athletes (Thomas et al. 1984; Rowan et al. 2012; Sandvei et al. 2012). Moreover, the decrease in RER (0.02–0.04 units) at 3 submaximal velocities (workloads I–III) below LT in the MICR group, which indicates enhanced fat oxidation, is in accordance with the results by Ulloa et al. (2015), who found enhanced maximal fat oxidation rate following 8 weeks of MICR (5–6 km, 3 times a week, ~62% $\dot{V}O_{2max}$) in recreational runners. The small nonsignificant increase (0.4%–1.8%) in absolute $\dot{V}O_2$ ($L \cdot min^{-1}$) at the same 3 submaximal velocities (workloads I–III) in the MICR group may support the decreased RER and a possible increase in fat oxidation in this (MICR) group, as decreases in respiratory quotient (RQ) from 0.95 to 0.91, 0.92 to 0.89, and 0.91 to 0.89 (i.e., an average increase in fat oxidation from ~25% to ~35% of the total energy turnover) at a given workload (for a given energy yield) increase the $\dot{V}O_2$ demand, theoretically, by ~0.5%–1.0% (McArdle et al. 2015, p. 188).

In contrast to the results in the MICR groups (~24 min at 85% HR_{max}, or 45 min at 70% HR_{max}) in the study by Helgerud et al. (2007), who improved their running economy, the MICR group in the present study showed a tendency towards increased energy cost of running. However, improved running economy is to be expected in previously nonrunning-trained subjects suddenly performing a relatively large amount of running exercise (Helgerud et al. 2007). Therefore, an explanation for the contradictory findings regarding the energy cost of running could be the fact that the participants in the present study were used to performing running exercise regularly, unlike those in the study by Helgerud et al. (2007). Furthermore, the possible increase in fat oxidation, and thereby the slightly higher absolute submaximal $\dot{V}O_2$, observed in the MICR group in the present study may also partially explain the discrepant results regarding the energy cost of running in the MICR group in the present study versus the MICR groups in the study by Helgerud et al. (2007).

High-intensity versus moderate-intensity running exercise

The impact of different exercise intensities in the development of the aerobic endurance "key factor", $\dot{V}O_{2max}$, has been studied for decades. In this context, Helgerud et al. (2007) and others (Thomas et al. 1984; Wenger and Bell 1986) have reported that intensity of training cannot be compensated by longer duration. The findings in the present study point in the same direction as the results in the above-mentioned studies (Thomas et al. 1984; Wenger and Bell 1986; Helgerud et al. 2007), as the HICR group increased absolute $\dot{V}O_{2max}$ significantly, whereas the MICR group did not (Table 1). Furthermore, the tendency towards increased $v\dot{V}O_{2max}$ observed in the HICR group, which was substantial and superior to that of the MICR group, is in accordance with the results in the study by Enoksen et al. (2011), who found that "high-intensity low-volume" training (82%–92% HR_{max}) improved $v\dot{V}O_{2max}$ more than "high-volume low-intensity" training (65%–82% HR_{max}) in middle-distance runners. This indicates that intensity of training may also be crucial in the development of $v\dot{V}O_{2max}$. On the other hand, among professional and some recreational runners, the main purpose of aerobic training is to improve running performance. In such a context, the findings of an equal increase in time to exhaustion in the HICR and MICR groups of the present study indicates that intensity of training can be compensated by longer duration. Therefore, based on the findings in the present study, both high- and moderate-intensity running exercise can be recommended in training regimes aimed at improving running performance and aerobic endurance. However, among recreational athletes with limited amount of time to spend on physical training, high-intensity aerobic running exercise (HIIR and/or HICR) can be a time-saving alternative.

HIIR versus HICR

In most studies aimed at investigating the training effects of high-intensity aerobic running exercise, HIIR has been the preferred modality (e.g., Thomas et al. 1984; Olsen et al. 1988; Esfarjani and Laursen 2007; Helgerud et al. 2007; Ulloa et al. 2015). Also, in practice, HIIR seems to be a favoured modality among recreational and competitive athletes, owing to its intermittent character (which gives the athlete breaks "to look forward to"), time-efficiency, and rapid improvement of performance and aerobic endurance. HICR, on the other hand, allows the athlete to exercise at high-training intensity without spending time on breaks. Thus, within a given total exercise time, including identical warm-up and recovery, HICR enables the athlete to achieve a larger amount of effective training (i.e., longer effective running distance) at high exercise intensity, in comparison with HIIR. An example of this was shown by Franch et al. (1998), which may have been a contributing factor to the greater enhancement of performance (94%) following HICR (~6381 m, 20–30 min, ~15.0 km·h⁻¹/~93% HR_{max}), than the performance improvement (67%) following HIIR (~5664 m, 4–6 times 4 min/2 min pauses, ~16.6 km·h⁻¹/~94% HR_{max}) observed in that particular study. Therefore, if the purpose is to improve running performance as much as possible, within a given total exercise time available (including warm-up and recovery), HICR may be recommended instead of HIIR. However, as only 1 study (Franch et al. 1998) appears to have addressed this issue, further research is needed to produce more scientific evidence about the performance and physiological effects of HIIR versus HICR.

Women versus men

In the present study, women and men were pooled in the training (HICR and MICR) and C groups, which may be debatable since women have systematically lower $\dot{V}O_{2max}$ than men (Edvardsen et al. 2013), and perform at a lower level than men in endurance sport events (Åstrand et al. 2003, p. 269). However, women and men with the same exercise status at pretraining seem to respond similarly physiologically ($\dot{V}O_{2max}$) to a given aerobic training stimulus (Thomas et al. 1984; Chandler et al. 1996). Therefore, as the women and men in the present study had approximately similar exercise status and relative $\dot{V}O_{2max}$ (mL·kg⁻¹·min⁻¹) at pretraining compared with normative data for age group and sex, the use of pooled groups of women and men should not have been a disadvantage in this case.

Limitations

In the present study, the number of subjects was relatively low in each group, which limited parts of the statistical analysis performed. For example, with a higher number of participants, the significant increases in time to exhaustion within the HICR and MICR groups would most likely also have been significantly greater than the change in time to exhaustion in the C group at pre- to post-training. Moreover, with larger groups, it is not unlikely that the changes in the main physiological variables, $\dot{V}O_{2max}$, LT, and/or running economy, as well as RER submaximally, would have differed significantly between the groups at pre- to post-training.

The participants' usual aerobic exercise pattern and intensity prior to the present study was not logged. Therefore, although the C group did not show any performance or physiological changes, it cannot be completely excluded that possible alterations in habitual exercise routines during the study might have influenced the training effects in the HICR and/or MICR groups.

In the present study, time to exhaustion during the ramp test pre- and post-training was used to evaluate changes in running performance. To the best of our knowledge, no studies have investigated the reliability of time to exhaustion in this ramp test procedure. However, it has been shown that exhaustive treadmill protocols, lasting approximately 6 to 7 min, running at $v\dot{V}O_{2max}$, and 1500-m time-trial time, may have a coefficient of variation (CV) of ~13%–17% (Currell and Jeukendrup 2008). Shorter time-to-exhaustion protocols (~1–2.5 min) performed at supramaximal workloads (120%–125% $\dot{V}O_{2max}$/150% of peak power output) have been shown to have a CV of ~2%–10% (Currell and Jeukendrup 2008). Thus, as the ramp test in the present study lasted ~4–8 min and was completed at a supramaximal velocity (~125% pretraining $\dot{V}O_{2max}$), it is not unreasonable to expect a time-to-exhaustion CV of ~10% in this ramp test. However, this issue remains to be investigated. Therefore, although time to exhaustion was improved by >20% in the HICR and MICR groups, with no changes in the C group, the performance effects in the 2 training groups (HICR and MICR) must be interpreted with caution.

There may also be some limitations to be considered with respect to the interpretation of substrate utilization. Although indirect calorimetry has been shown to accurately determine substrate oxidation at exercise intensities up to ~75%–85% $\dot{V}O_{2max}$ (Jeukendrup and Wallis 2005), it is important to be aware that overbreathing, where CO_2 "blows off" from the lungs, or additional CO_2 from increasing reliance on lactic anaerobic metabolism above ~60%–65% $\dot{V}O_{2max}$, generates a rise in RER that does not reflect RQ from aerobic metabolism (McArdle et al. 2015, pp. 189, 290–291). Furthermore, the type, amount, and timing of nutrient intake before exercise are also factors that may influence substrate oxidation (Achten and Jeukendrup 2004). However, the nutrient intake was not assessed prior to the exercise tests in the present study. Therefore, the results of the present study regarding RER must also be interpreted with caution.

Practical implications

Previous studies have shown that ~25–45 min of moderate-intensity continuous (70%–85% HR_{peak}/HR_{max}) and/or 4–6 times 4 min of high-intensity interval training (85%–95% HR_{peak}/HR_{max}), 2 to 3 times a week, for 6–12 weeks, can improve performance and/or aerobic endurance significantly in both cardiac (Wisløff et al. 2007; Helgerud et al. 2011) and pulmonary patients (Bjørgen et al. 2009), in moderately trained individuals (Franch et al. 1998; Helgerud et al. 2007) and in soccer players at a relatively high competitive level (Helgerud et al. 2001). It is, therefore, not unreasonable to believe that the 2 training modalities (HICR and MICR) successfully examined in moderately trained recreational athletes in the present study may produce performance and physiological gains also in different patients undergoing rehabilitation, as well as healthy untrained individuals and athletes competing at higher levels in various endurance and team sports. In this context, it is important to emphasize that the exercise duration and training frequency must be customized individually, based on the initial fitness level of the subject(s). This probably implies shorter training duration during HICR (<20 min) and MICR (<40 min) in patients and untrained individuals, initially, whereas longer exercise duration (HICR: >20 min, MICR: >40 min), higher training intensity (HICR: >88% HR_{max}, MICR: >80% HR_{max}), and/or more frequent exercise frequency (>3 times per week), than used in the present study, may be necessary in high-level endurance and team sport athletes to gain performance and aerobic endurance effects. However, when it comes to HICR, this remains to be further investigated, as the scientific evidence about the training effects of this modality (HICR) appears to be nonexistent in patients, healthy untrained individuals, and high-level endurance and team sport athletes.

Conclusions

The present study indicates that even with a substantially lower total energy turnover, HICR can be as performance enhancing as MICR. Moreover, HICR can increase maximal aerobic power, whereas MICR may enhance fat oxidation.

Conflict of interest statement

The authors have no conflicts of interest to report.

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