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JOURNAL OF SPORTS SCIENCES, 2016
http://dx.doi.org/10.1080/02640414.2016.1209539

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HIIT enhances endurance performance and aerobic characteristics more than high-volume training in trained rowers

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ABSTRACT

This study compared the effects of long~~,~~ slow distance training (LSD) with high-intensity interval training (HIIT) in rowers. Nineteen well-trained rowers performed three tests before and after an 8-week training intervention: (1) 2000 m time trial; (2) seven-stage incremental step test to determine maximum oxygen uptake ($\dot{V}O_{2max}$), power output at $\dot{V}O_{2max}$ ($W\dot{V}O_{2max}$), peak power output (PPO), rowing economy and blood lactate indices and (3) seven-stroke power-output test to determine maximal power output (W_{max}) and force (F_{max}). After baseline testing, participants were randomly assigned either to a HIIT or LSD group. The LSD comprised 10 weekly aerobic sessions. The HIIT also comprised 10 weekly sessions: 8 aerobic and 2 HIIT. The HIIT sessions comprised 6–8 × 2.5 min intervals at 100% PPO with recovery time based on heart rate (HR) returning to 70% HR_{max}. Results demonstrated that the HIIT produced greater improvement in 2000 m time trial performance than the LSD (effect size (ES) = 0.25). Moreover, the HIIT produced greater improvements in $\dot{V}O_{2max}$ (ES = 0.95, $P = 0.035$) and power output at lactate threshold (W_{LT}) (ES = 1.15, $P = 0.008$). Eight weeks of HIIT performed at 100% PPO is more effective than LSD in improving performance and aerobic characteristics in well-trained rowers.

ARTICLE HISTORY
Accepted 28 June 2016

KEYWORDS
High-intensity interval training; rowing; athletic performance; VO_{2max}

Introduction

Physiological attributes of rowers are among the highest recorded for any sport (Hagerman, Hagerman, & Mickelson, 1979; Nevill et al., 2003) with rowing highlighting the challenge of simultaneously developing both endurance and strength (Babraj & Volianitis, 2007). During a 2000 m rowing race, exceptionally high demands are placed both on aerobic and anaerobic energy systems (Hagerman, 1984) and during competition, rowers exercise at severe intensities with the majority of exercise performed at 95–98% of maximal rowing capacity (Hagerman, Connors, Gault, Hagerman, & Polinski, 1978). Despite this, most training completed by rowers is performed below the blood lactate threshold (Steinacker, 1993) with little emphasis placed on training at 80–100% $\dot{V}O_{2max}$, which could be achieved through high-intensity interval training (HIIT).

There is an increasing body of evidence that HIIT improves performance and aerobic capability in well-trained athletes from a variety of endurance sports (Robinson, Robinson, Hume, & Hopkins, 1991; Wenger & Bell, 1986) including endurance running (Smith, Coombes, & Geraghty, 2003; Smith, McNaughton, & Marshall, 1999) and cycling (Lindsay et al., 1996; Westgarth-Taylor et al., 1997; Weston et al., ~~1996~~). Despite this, there is little information on effects of HIIT on well-trained rowers where traditional long~~,~~ slow distance training (LSD) predominates. In the only published ~~study,~~ Driller, Fell, Gregory, Shing and Williams (2009) examined effects of HIIT in well-trained rowers and reported that 4 weeks of HIIT was associated with greater improvements in time-trial performance and relative peak rate of oxygen uptake ($\dot{V}O_{2peak}$) than with traditional rowing training.

Mechanisms responsible for performance improvements with HIIT in well-trained athletes remain equivocal. Purported mechanisms include: increased activity of mitochondrial enzymes (Burgomaster, Hughes, Heigenhauser, Bradwell, & Gibala, 2005), reduced glycogen utilisation and lactate accumulation during exercise of similar intensity (Burgomaster, Heigenhauser, & Gibala, 2006), improved ventilatory threshold (Laursen, Shing, Peake, Coombes, & Jenkins, 2005), enhanced fat oxidation (Westgarth-Taylor et al., 1997), increased anaerobic capabilities (Laursen et al., 2005) and increased buffering capacity (Weston et al., ~~1996~~). The ability to buffer H^+ accumulation could be an important determinant of high-intensity exercise performance as a greater buffering capacity should allow anaerobic glycolysis to continue during maximal- and high-intensity exercise, resulting in a larger lactate production without an associated increase in H^+ accumulation (Edge, Bishop, Hill-Haas, Dawson, & Goodman, 2006).

Combining large volumes of LSD with judicious use of HIIT has been suggested as the best-practice model for the development of endurance performance (Seiler & Tonnessen, 2009). Despite this, few studies have investigated the use of HIIT in well-trained rowers (Driller et al., 2009). While some evidence indicates that performance of HIIT in addition to traditional

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LSD is beneficial for well-trained endurance athletes, there is a need for a controlled training intervention study with well-trained rowers. The aim of this study was to compare effects of HIIT and LSD in well-trained rowers. Buffering capacity has not previously been researched in rowing and HIIT, therefore the role of buffering capacity as an underlying mechanism to any physiological or performance enhancements was a focus.

Methods

Participants

Nineteen well-trained rowers (14 men and 5 women, age 22 ± 4 years, stature 185 ± 6.3 cm, body mass 83.9 ± 9.8 kg) participated in the study and were required to have been free from injury and in a national-standard training programme for a minimum of 3 years. Participants were fully informed in writing of the requirements and potential risks and benefits of participating before providing written informed consent and completing a pre-test questionnaire. All experimental procedures were approved by the local University Ethics Committee.

Research design

After a week of baseline testing including anthropometry, a 2000 m time trial, an incremental step test and a seven-stroke power-output test, participants were randomly assigned to 1 of 2 groups: a LSD group and a HIIT group, and completed an 8-week controlled training block. All tests were performed under the supervision of the principal investigator in a designated high performance laboratory, on a Concept II model C air-braked rowing ergometer (Concept II, Nottingham, England). Tests after training were conducted in the same order and at the same time of the day as those before. Participants were requested to follow strict protocols for 24 h before test days including maintaining a normal diet, optimising hydration, refraining from alcohol and undertaking no more than 30 min of light training.

Anthropometry

Body mass was assessed to the nearest 0.1 kg (Seca 799, Hamburg, Germany) and stature was measured to the nearest 0.1 cm (Seca 217, Hamburg, Germany). Body composition was assessed using skinfold thickness and dual-energy X-ray absorptiometry (DXA). Skinfold thickness was measured to the nearest 0.1 mm in accordance with the International Society for the Advancement of Kinanthropometry (ISAK) protocols (Norton et al., 2006), using Harpenden callipers (Baty International, West Sussex, UK) calibrated as per the manufacturer's guidelines. Skinfold thickness was measured on the right side of the body at 7 sites (biceps, triceps, subscapular, supraspinale, abdominal, frontal thigh and medial calf), by the same Level 1 ISAK accredited investigator with a technical error of measurement of 1.1% for the sum of the 7 skinfolds. The DXA calculated percentage body fat (BF %). A Lunar iDXA™ scanner (GE Healthcare, Chalfont St Giles, Bucks., UK) with enCORE™ 2011 v.13.6 software captured total body composition scans. Calibration of the scanner, with use of a phantom spine as per the manufacturer's guidelines, was carried out daily.

2000 m time trial

The 2000 m time trial was performed on the first day of testing immediately after a self-selected warm-up. 2000 m rowing ergometer time trials are an integral part of rowing assessment and selection and all participants were fully habituated to the performance of 2000 m time trials. The test–retest reliability of 2000 m time trials on the Concept II model C has previously been examined with well-trained rowers, with a coefficient of variation of 0.6% being reported (Schabort, Hawley, Hopkins, & Blum, 1999). Single earlobe blood samples (5 µL) were taken to determine blood lactate concentration before and 5 min after the time trial using a portable blood lactate analyser calibrated in accordance with the manufacturer's guidelines (Lactate Pro, Arkray Factory Inc, Shiga, Japan). A finger-prick blood sample (100 µL) was taken before and 5 min after the time trial to determine pH and bicarbonate (HCO_3), using a blood-gas analyser calibrated as per manufacturer's guidelines (i-Stat, Abbott Point of Care, Princeton, NJ). Heart rate was measured continuously (RS400, Polar Electro OY Finland) during the performance.

Incremental step test

The incremental step test was completed 48 h after the time trial. The seven-stage test was performed according to the Australian physiological assessment of rowing guidelines (Tanner & Gore, 2000) and determined maximum oxygen uptake ($\dot{V}O_{2max}$), power output at $\dot{V}O_{2max}$ ($W\dot{V}O_{2max}$), 4 min all-out power output (PPO), rowing economy, power output at lactate threshold (W_{LT}), percentage $\dot{V}O_{2max}$ at lactate threshold, maximum heart rate, peak lactate (peak La) and power outputs associated with blood lactate concentrations of 2 ($W_{2\ mmol/l}$) and 4 mmol.l^{-1} ($W_{4\ mmol/l}$). Mean submaximal heart rates were identified over the final 30 s of each exercise intensity and maximum heart rate was the highest recorded value. The mean power output achieved during the final 4 min bout was identified as PPO. The $W\dot{V}O_{2max}$ was calculated using the regression equation describing $\dot{V}O_2$ and power output for the 6 incremental stages (Ingham, Whyte, Jones, & Nevill, 2002). Economy was expressed as mean oxygen uptake per watt (ml·W^{-1}) of the submaximal stages below lactate threshold (Nevill, Allen, & Ingham, 2011).

Gas analysis

Expired air was continuously analysed for O_2 and CO_2 concentrations using an online gas collection system (Moxus modular oxygen uptake system, AEI technologies, Pittsburgh, PA) with mean values recorded over 30 s intervals. Before each test, the analysers were calibrated as per the manufacturer's guidelines with gases of known concentration (15.99% O_2 and 4.04% CO_2) and the pneumotach was calibrated with a 3-l syringe. Submaximal oxygen uptakes were the mean of recordings during the final 2 min of each submaximal exercise intensity. The $\dot{V}O_{2max}$ was identified as the mean of the highest 2 consecutive readings in the final bout.

Blood lactate and blood gas analysis

An earlobe blood sample (5 µL) was taken using a lactate analyser (Lactate Pro, Arkray Factory Inc, Shiga, Japan) to determine pre-test blood lactate and a sample was taken immediately at the end of each 4 min bout in addition to 2 and 5 min after the final bout. The lactate analyser was calibrated as per the manufacturer's guidelines immediately before each incremental test. All blood lactate plots were examined both manually and with the use of Lactate-E, software for blood lactate endurance markers (Newell et al., 2007), to identify the lactate threshold and the power outputs associated with 2 ($W_{2 mmol/l}$) and 4 mmol.l^{-1} ($W_{4 mmol/l}$). Because fixed blood lactate concentrations do not take into account individual kinetics of the blood lactate curve and marked individual variations in these threshold values have been reported (Stegmann & Kindermann, 1982), the lactate threshold was also identified using the ADAPT method (Bourdon, 2000).

Before and 5 min after the incremental test, a finger-prick blood sample (100 µL) was taken to determine pH and HCO_3, using a blood-gas analyser calibrated as per the manufacturer's guidelines (i-Stat, Abbott Point of Care, Princeton, NJ).

Seven-stroke power-output test

The seven-stroke power-output test was completed on the final day of testing. Force profiles and power output were determined for each stroke using a force transducer attached to the handle of the rowing ergometer and a PowerLab Data Acquisition System (AD Instruments, Oxford, UK). After a standardised warm-up (Godfrey & Williams, 2006), participants performed a seven-stroke maximum power-output test at 30 strokes per min. Maximum force (F_{max}), maximum power output (W_{max}) and stroke rate were expressed as the mean value over the final 5 recorded strokes; the first 2 were not recorded as the rower overcame frictional forces and brought the flywheel to operational velocities (Winter & Fowler, 2009).

Training intervention

The study was conducted during the preparation phase of the participant's yearly training programme. Participants were randomly divided into 1 of 2 training groups, HIIT or LSD and completed detailed daily training diaries. Training for both groups comprised a combination of on-water and ergometer training that typically involved 6 on-water sessions and 4 ergometer sessions per week. The LSD group maintained their current training of 10 sessions per week. Using the results of the incremental step test, individual training zones were identified for each participant based on lactate and heart rate responses. Training zones identified included recovery, extensive aerobic, intensive aerobic, threshold and max/anaerobic zones, and were used in the individualised prescription of intensity for all training sessions for both training groups (Bourdon, 2000). The intensity of training sessions was controlled using heart rate during on-water sessions and heart rate and power output during ergometer sessions. The LSD group completed 8 extensive aerobic sessions, for example 90 min on-water rowing in the extensive aerobic zone, and 2 intensive aerobic sessions, for example three 10 min on-water or ergometer pieces in the intensive aerobic zone. The HIIT group also completed 10 training sessions per week, however, 2 extensive aerobic sessions per week were replaced with 2 HIIT sessions (Esfarjani & Laursen, 2007) and 16 HIIT sessions were completed in total, all of which were completed on the ergometer. These sessions were at least 48 h apart and performed at 100% PPO, as identified in the incremental step test. During weeks 1 and 2, 6 intervals of ~~2·5~~ min were completed in each session, 7 were completed in weeks 3 and 4 and 8 from weeks 5 to 8. Recovery involved rowing at 40% PPO until heart rate returned to ≤70% of its maximum (Driller et al., 2009).

Statistical analysis

All statistical calculations were performed using PASW software V.20.0 (SPSS, Chicago, Illinois, USA). Means and standard deviations were calculated for all variables. Normality of the data was verified using the Shapiro–Wilk test. A mixed-design factorial analysis of variance (ANOVA) (time [before and after] x group [HIIT and LSD]) compared groups. A mixed-design factorial ANOVA (time [before and after] x sex [male and female]) was also used to ensure there was no sex-related effect on the participant's responses to training over time. Statistical significance was set at $P < 0.05$ for all analyses. Effect sizes (ES) were determined using Cohen's *dz*, defined as the difference between the mean of the difference scores divided by the standard deviation of the difference scores. The magnitude of the ES was classified as large (≥0.80), moderate (0.50–0.79), small (<0.20–0.49) or trivial (0–0.19) (Cohen, 1988).

Results

The anthropometric characteristics of the participants are presented in Table 1. The HIIT resulted in a greater decrease in BF

Table 1. Anthropometric characteristics of participants.

	LSD (*n* = 9)				HIIT (*n* = 10)				
Variable	Before	After	%Δ	90% CI	Before	After	%Δ	90% CI	ES
Body mass (kg)	83.0 ± 11.7	82.8 ± 11.0	−0.2	−0.71/1.11	85.0 ± 7.9	85.0 ± 7.5	0.0	−1.06/1.08	0.04
Skinfold (mm)	84.9 ± 41.2	77.2 ± 32.0	−8.6	−0.05/2.85	85.4 ± 35.2	78.0 ± 31.0	−9.1**	0.59/2.04	0.12
BF (%)	20.1 ± 7.9	19.3 ± 7.3	−3.7	0.05/1.43	20.3 ± 6.8	18.8 ± 7.4	−7.4**	0.8/2.18	0.63

Data presented as mean ± *s*, percentage change (%Δ) and 90% confidence intervals (CI). ES effect size. $^{**}P < 0.01$ (within group). BF body fat.

% than the LSD (ES = 0.63). After 8 weeks BF% decreased from 20.3 ± 6.8% to 18.8 ± 7.4% ($P = 0.004$) after the HIIT and from 20.1 ± 7.9% to 19.3 ± 7.3% after the LSD.

Physiological and performance responses

Table 2 presents the training-related changes in physiological and performance measures. The HIIT was associated with a greater improvement in 2000 m time trial performance than the LSD (ES = 0.25) with the HIIT improving 2000 m time trial performance from 407.2 ± 23.2 s before the training to 400.2 ± 22.6 s after the training (−1.7%, 90% CI = 3.03/10.99 s, $P = 0.011$) and the LSD resulting in a smaller improvement in performance from 415.6 ± 38.1 s before the training to 411 ± 31.2 s after the training (−1.1%, 90% CI = −2.07/11.36 s, $P = 0.237$). The HIIT resulted in a greater improvement in $\dot{V}O_{2max}$, than the LSD (ES = 0.95, $P = 0.035$). The HIIT also resulted in an improvement in W_{LT} (17.3%, 90% CI = −41.6/−14.39 W, $P = 0.005$) and percentage $\dot{V}O_{2max}$ at LT (3.7%, 90% CI = −6.04/−1.43 W, $P = 0.017$) with the improvement after the HIIT greater than the improvements after the LSD for W_{LT} and $\dot{V}O_{2max}$ at LT (ES = 1.15, $P = 0.008$, and ES = 1.09, $P = 0.012$, respectively). The HIIT was also associated with greater improvements in $W_{2\,mmol/l}$ and $W_{4\,mmol/l}$ (ES = 0.53 and ES = 0.42, respectively) and $W\dot{V}O_{2max}$ and economy (ES = 0.72 and ES = 0.71, respectively) than the LSD.

Buffering capacity

There were no training-induced improvements in blood buffering capacity after the HIIT or the LSD. The LSD resulted in a greater decrease in resting pH than the HIIT (ES = 0.94, $P = 0.036$) but no difference was observed in resting HCO_3 (ES = 0.19, $P = 0.680$) or blood buffering capacity after the 2000 m time trial or incremental step test as identified through peak blood lactate (ES = 0.39, $P = 0.410$ and ES = 0.36, $P = 0.444$, respectively), post exercise pH (ES = 0.005, $P = 0.991$ and ES = 0.08, $P = 0.868$,) or post exercise HCO_3 (ES = 0.15, $P = 0.760$ and ES = 0.03, $P = 0.943$) (Table 3).

Discussion

Aerobic training has traditionally been the focus for well-trained rowers who, similar to other endurance athletes, perform ~75% of training at intensities below the lactate threshold, despite competing at much higher intensities (Esteve-Lanao, Foster, Seiler, & Lucia, 2007). However, improvements in performance become difficult to attain for highly-trained athletes and additional increases in aerobic training might not improve endurance performance or associated physiological variables (Billat et al., 2001). It has therefore been suggested that the combination of traditional endurance training and HIIT could optimise the development of aerobic muscle characteristics and enhance performance (Laursen, 2010).

Table 2. Performance and physiological variables measured before and after 8 weeks training.

	LSD ($n = 9$)				HIIT ($n = 10$)				
Variable	Before	After	%Δ	90% CI	Before	After	%Δ	90% CI	ES
2000 m TT (s)	415.6 ± 38.1	411.0 ± 31.2	−1.1	−2.07/11.36	407.2 ± 23.2	400.2 ± 22.6	−1.7*	3.03/10.99	0.25
$\dot{V}O_{2max}$ (l.min^{-1})	4.62 ± 0.95	4.54 ± 0.83	−1.7	−0.04/0.19	4.71 ± 0.61	5.01 ± 0.67	+6.4†	−0.6/−0.003	0.95
$W\text{-}\dot{V}O_{2max}$ (W)	298 ± 64	301 ± 57	1.2	−9.25/2.05	305 ± 41	321 ± 45	+5.1	−28.69/−2.64	0.72
Economy (ml·W^{-1})	13.4 ± 1.8	12.96 ± 1.86	−3.1	0.04/0.8	12.7 ± 1.2	12.7 ± 1.1	+0.1	−0.31/0.29	0.71
W_{LT} (W)	156 ± 34	158 ± 31	+1.2	−11.09/7.49	162 ± 35	190 ± 37	+17.3**†	−41.6/−14.39	1.15
$W_{2\,mmol/l}$ (W)	180 ± 42	199 ± 44	+10.7**	−29.01/−9.39	198 ± 40	226 ± 41	+14.2**	−38.3/−17.92	0.53
$W_{4\,mmol/l}$ (W)	227 ± 49	244 ± 51	+7.5***	−22.47/−11.54	245 ± 39	267.4 ± 44	+9.1**	−31.71/−12.73	0.42
W_{max} (W)	453 ± 97	452 ± 89	−0.3	−16.92/19.32	475 ± 87	488.2 ± 72	+2.7	−39.7/14.15	0.37
F_{max} (N)	1124 ± 176	1157 ± 169	+2.9*	−51.26/−13.41	1142 ± 166	1181 ± 143	+3.4	−80.3/2.46	0.13
PPO (W)	311 ± 72	325 ± 67	+4.6	−26.2/−2.4	338 ± 54	359 ± 56	+6.3*	−34.41/−8.03	0.34
%$\dot{V}O_{2max}$@LT	61.7 ± 6.6	60.4 ± 7.5	−1.3	−1.08/3.58	60.6 ± 5.3	63.9 ± 2.6	+3.7*†	−6.04/−1.43	1.09

Data presented as mean ± *s*, percentage change (%Δ) and 90% confidence intervals (CI). ES = effect size.***$P < 0.001$; **$P < 0.01$; *$P < 0.05$ (within group). †$P < 0.05$ (between groups). 2000 m TT = 2000 m time trial, $\dot{V}O_{2max}$ = maximum oxygen uptake, $W\,\dot{V}O_{2max}$: power at $\dot{V}O_{2max}$, W_{LT}: power at lactate threshold, $W_{2\,mmol/l}$: power output at 2 mmol.l^{-1}, $W_{4\,mmol/l}$: power output at 4 mmol.l^{-1}, W_{max}: maximum power, F_{max}: maximum force, PPO: peak power output, %$\dot{V}O_{2max}$@LT: percentage $\dot{V}O_{2max}$ at the lactate threshold.

Table 3. Blood buffering capacity variables measured before and after 8 weeks training.

	LSD ($n = 9$)				HIIT ($n = 10$)				
Variable	Pre	Post	%Δ	90% CI	Pre	Post	%Δ	90% CI	ES
Resting pH	7.43 ± 0.02	7.41 ± 0.01	−0.1*†	0.002/0.019	7.4 ± 0.02	7.42 ± 0.02	+0.2	−0.03/0.005	0.94
Resting HCO_3 (mmol.l^{-1})	24.4 ± 1.4	25.02 ± 1.9	+2.5	−0.48/0.48	24.96 ± 2.55	25.28 ± 1.9	+1.3	−0.64/0.62	0.19
Step Peak La (mmol.l^{-1})	13.3 ± 2.4	12.8 ± 2.0	−3.9	−0.44/1.48	13.7 ± 1.8	12.6 ± 1.9	−8.00	0.13/2.07	0.36
2k Peak La (mmol.l^{-1})	13.1 ± 2.6	12.1 ± 2.1	−8.2	−0.62/2.76	12.4 ± 2.3	12.4 ± 2.3	−0.1	−1.55/1.56	0.39
Step post pH	7.11 ± 0.09	7.11 ± 0.09	0.0	−0.02/0.03	7.10 ± 0.75	7.09 ± 0.07	−0.1	−0.03/0.04	0.08
2k post pH	7.03 ± 0.08	7.03 ± 0.08	0.0	−0.04/0.04	7.06 ± 0.11	7.06 ± 0.09	0.0	−0.04/0.04	0.01
Step post HCO_3 (mmol.l^{-1})	9.47 ± 1.97	9.35 ± 2.19	−1.3	−0.50/0.74	8.93 ± 2.01	8.87 ± 2.26	−0.8	−1.19/1.33	0.03
2k HCO_3 post (mmol.l^{-1})	7.03 ± 1.11	7.87 ± 1.88	+12.0	−2.0/0.32	7.52 ± 2.69	8.11 ± 1.87	+7.8	−1.51/0.87	0.15

Data presented as mean ± *s*, percentage change (%Δ) and 90% confidence intervals (CI). ES: effect size. *$P < 0.05$ (within group). †$P < 0.05$ (between groups). Step Peak La: peak lactate after step test, 2k Peak La: peak lactate after 2000 m time trial, Step post pH: pH after step test, 2k post pH: pH after 2000 m time trial, Step post HCO_3: HCO_3 after step test, 2k post HCO_3: HCO_3 after 2000 m time trial.

Improvements in performance in running (Acevedo & Goldfarb, 1989; Smith et al., 1999) and cycling (Laursen, Shing, Peake, Coombes, & Jenkins, 2002; Lindsay et al., 1996) have been reported after HIIT but there is little research on effects of HIIT on rowing performance. The results of this present study demonstrated that the HIIT produced greater improvement in 2000 m time trial performance than the LSD (ES = 0.25). From a practical perspective the HIIT was associated with a mean improvement of 7 s (−1.7%), comparable to 4.25 boat lengths in a single scull 2000 m race, while the LSD resulted in a mean improvement of 4.6 s (−1.1%) comparable to 2.75 boat lengths. This improvement after the HIIT was similar to that reported by Driller et al. (2009), who reported an 8.2 (± 3.8) s improvement in 2000 m time-trial performance after 4 weeks of high-intensity interval training compared with a mean improvement of 2.3 (± 5) s after 4 weeks of traditional rowing training. The present study involved 8 weeks of HIIT training while Driller et al. (2009) used a shorter duration of 4 weeks. This indicates that a shorter duration is sufficient to elicit an improvement in 2000 m rowing performance in well-trained rowers through the use of HIIT. Little information is available about the rate at which endurance performance improves after HIIT. Studies have reported improvements in endurance performance after 3 (Stepto, Hawley, Dennis, & Hopkins, 1999), 4 (Laursen et al., 2005; Smith et al., 1999), 6 (Westgarth-Taylor et al., 1997) and 8 weeks (Acevedo & Goldfarb, 1989) of HIIT. However, control groups were not used in all HIIT studies which make improvements in performance difficult to interpret and given the dearth of research into effects of HIIT on rowers, further research to identify optimal HIIT protocols is required.

$\dot{V}O_{2max}$ has previously been shown to be an important predictor of 2000 m rowing performance (Cosgrove, Wilson, Watt, & Grant, 1999; Ingham et al., 2002). HIIT has been reported to be effective at increasing $\dot{V}O_{2max}$ in untrained participants (MacDougall et al., 1998; Tabata et al., 1996). However, effects of HIIT on $\dot{V}O_{2max}$ in well-trained athletes is equivocal (Billat, Demarle, Paiva, & Koralsztein, 2002a; Laursen et al., 2005). Improvements in $\dot{V}O_{2max}$ could occur through increases in oxygen delivery and/or oxygen utilisation by active muscles (Holloszy & Coyle, 1984). In this study, absolute $\dot{V}O_{2max}$ improved more in the HIIT group (6.4%) than the LSD (−1.7%) (ES = 0.95, $P = 0.035$), similar to that reported for other studies (Billat et al., 2002a; Laursen et al., 2002). Billat et al. (2002a) reported an improvement in $\dot{V}O_{2max}$ of 5.4% in elite marathon runners after 8 weeks of HIIT while Laursen et al. (2002) reported an 8% improvement in $\dot{V}O_{2max}$ after 4 weeks of HIIT. The improvement in $\dot{V}O_{2max}$ in this study suggests effects of HIIT on $\dot{V}O_{2max}$ depend on the intensity of the intervals performed, with HIIT sessions at PPO (approximately 10% above the power corresponding to $\dot{V}O_{2max}$) appearing to be the most effective at eliciting improvements in $\dot{V}O_{2max}$ in already well-trained athletes.

The accumulation of blood lactate during incremental exercise tests is a measure commonly used to evaluate effects of training, to establish individualised training intensities and to predict performance (Bourdon, 2000). The blood lactate response to exercise is a more sensitive indicator of endurance performance than $\dot{V}O_{2max}$ (Weltman, 1995) and it has been demonstrated that indices of blood lactate during submaximal exercise and the ability to elicit less lactate for a given power output are highly correlated with rowing performance (Cosgrove et al., 1999; Ingham et al., 2002; Messonnier, Freund, Bourdin, Belli, & Lacour, 1997). The present study identified greater improvement in W_{LT} after 8 weeks of HIIT than from LSD (ES = 1.15, $P = 0.008$). A 17.3% improvement in W_{LT} occurred after the HIIT (28 W, $P = 0.005$) compared with a 1.2% improvement after the LSD (2 W, $P = 0.731$). Training below the lactate threshold typically predominates rowing training programmes, however, the results from the present study are in agreement with previous research (Ingham, Carter, Whyte, & Doust, 2008), suggesting that training above the lactate threshold can stimulate the development of the lactate response in well-trained athletes. This is an important finding for training prescription as it indicates that HIIT does not compromise aerobic training adaptations. Indeed, it augments such adaptations. In running for instance, the speed at the lactate threshold is highly correlated with improvements in performance after HIIT (Billat, Mille-Hamard, Demarle, & Koralsztein, 2002b). Furthermore, it has been suggested that HIIT could delay the accumulation of lactate to a greater extent than LSD both by increasing the oxidative capacity and recruitment of muscle fibres (Poole & Gaesser, 1985) or HIIT might afford the ability to tolerate the presence of lactate, enhancing lactate removal and allowing better tolerance of high-intensity activity (Brooks, Fahey, White, & Baldwin, 2000).

Several studies have reported $W\dot{V}O_{2max}$ to be highly correlated with 2000 m rowing ergometer performance (Ingham et al., 2002; Nevill et al., 2011) and it has been suggested $W\dot{V}O_{2max}$ could be a valuable tool for monitoring endurance performance (Mikulic, 2011). Nevill et al. (2011) identified $W\dot{V}O_{2max}$ as the best single predictor of performance, explaining 95.3% of the variance in rowing speed in elite rowers. The results of this study are similar to previous studies (Billat, Flechet, Petit, Muriaux, & Koralsztein, 1999; Esfarjani & Laursen, 2007) and suggest that HIIT provides a better stimulus than LSD to improve $W\dot{V}O_{2max}$ (ES = 0.72). The HIIT improved $W\dot{V}O_{2max}$ by 5.1% (16 W) while the LSD group had a smaller improvement of 1.2% (4 W). Improvements in $W\dot{V}O_{2max}$ could be important for athletes who have reached a plateau in $\dot{V}O_{2max}$, as identified by Mikulic (2011) who reported that while $\dot{V}O_{2max}$ reached a plateau in elite-standard rowers, $W\dot{V}O_{2max}$ continued to increase.

Proposed mechanisms responsible for performance changes in well-trained athletes after HIIT are equivocal. An increase in buffering capacity is one such mechanism (Gibala et al., 2006; Weston et al., ~~1996~~). The ability of muscle to buffer increased concentrations of H^+ is an important factor during intense exercise and therefore those with a greater ability to regulate H^+ during intense exercise should be better able to maintain intense muscle contractions and it has been suggested that regular HIIT could result in an elevated buffering capacity (Edge et al., 2006). This is not supported in the present study with only changes in resting pH observed and no change in resting buffering capacity or post-exercise blood pH, HCO_3 or lactate for either group after 8 weeks of HIIT and LSD training. Differences in the results of studies into effects of HIIT on buffering capacity could be attributed to variations in exercise intensity, recovery periods or modes of training, or basal bicarbonate concentrations, all of which can affect H^+ accumulation (Edge et al., 2006). In this study it is possible that the length of recovery periods used between intervals could have inhibited an improvement in buffering capacity. A large accumulation of H^+ during HIIT sessions is suggested to be an important stimulus in the improvement of buffering capacity (Weston, Wilson, Noakes, & Myburgh, 1996) and the removal of H^+ during long recovery periods would reduce H^+ accumulation during training therefore reducing the potential to increase buffering capacity.

Conclusion

The results demonstrated that the HIIT produced greater improvement in 2000 m time trial performance than the LSD. The results also revealed that in addition to improved use of time, 8 weeks of HIIT produced greater improvements in aerobic characteristics, including $\dot{V}O_{2\max}$ and W_{LT}, than traditional training in well-trained rowers. These improvements could have important implications for training prescription as HIIT did not compromise aerobic adaptations and did in fact augment them. However further research is warranted using a larger sample size to optimise the HIIT training protocol for well-trained rowers, with regards the manipulation of frequency, intensity, recovery period and duration of both the intervals and HIIT programme. In contrast, blood buffering capacity as a mechanism underlying anaerobic adaptations associated with the HIIT revealed that blood buffering capacity was not altered after 8 weeks of training. Further research is required to investigate the underlying mechanisms responsible for performance and physiological changes associated with HIIT in rowers.

Acknowledgements

The authors wish to express their appreciation to the Irish Institute of Sport for the use of a High Performance Laboratory and equipment.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This project was funded by the Irish Research Council for Science Engineering and Technology.

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