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ORIGINAL ARTICLE

Performance and physiological responses to repeated-sprint exercise: a novel multiple-set approach

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Abstract We investigated the acute and chronic responses to multiple sets of repeated-sprint exercise (RSE), focusing on changes in acceleration, intermittent running capacity and physiological responses. Ten healthy young adults (7 males, 3 females) performed an incremental test, a Yo-Yo intermittent recovery test level1 (Yo-Yo IR1), and one session of RSE. RSE comprised three sets of 5 × 4-s maximal sprints on a non-motorised treadmill, with 20 s of passive recovery between repetitions and 4.5 min of passive recovery between sets. After ten repeated-sprint training sessions, participants repeated all tests. During RSE, performance was determined by measuring acceleration, mean and peak power/velocity. Recovery heart rate (HR), HR variability, and finger-tip capillary lactate concentration ($[Lac^-]$) were measured. Performance progressively decreased across the three sets of RSE, with the indices of repeated-sprint ability being impaired to a different extent before and after training. Training induced a significant increase ($p < 0.05$) in all indices of performance, particularly acceleration (21.9, 14.7 and 15.2% during sets 1, 2 and 3, respectively). Training significantly increased Yo-Yo IR1 performance by 8% and decreased $\Delta[Lac^-]$/work ratio (−15.2, −15.5, −9.4% during sets 1, 2 and 3, respectively) and recovery HR during RSE. There were strong correlations between Yo-Yo IR1 performance and indices of RSE performance, especially acceleration post-training ($r = 0.88$, $p = 0.004$). Repeated-sprint training, comprising only 10 min of exercise overall, effectively improved performance during multiple-set RSE. This exercise model better reflects team-sport activities than single-set RSE. The rapid training-induced improvement in acceleration, quantified here for the first time, has wide applications for professional and recreational sport activities.

Keywords Repeated-sprint ability · Acceleration · Recovery heart rate · Yo-Yo · Intermittent training

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Introduction

In many team sports, the number of sprints during a match is between 20 and 40, with an average duration of 2–3 s, and recovery periods ranging from ~50 to 300 s (Bangsbo et al. 1991; Dawson et al. 2004; Mohr et al. 2003; Spencer et al. 2004b). This combination of sprints and recovery is unlikely to be linked to a performance decrement during the game. When 6-s sprints are performed with 60 s of recovery, a decline in performance is only evident after the tenth consecutive repetition (Balsom et al. 1992). However, during a game sprints are often clustered, with short recovery between repetitions (i.e., <60 s) and longer recovery between bouts (Spencer et al. 2004b). These repeated-sprint bouts are typically associated with the important phases of the game, such as gaining advantage over an opponent or creating scoring opportunities.

Therefore, the ability to repeat sprints [i.e., repeated-sprint ability (Wadley and Le Rossignol 1998)], is fundamental for team-sport players.

A single set of 5–15 sprints, with between-sprint recovery of less than 30 s, has traditionally been used to assess performance during repeated-sprint exercise (RSE) (Spencer et al. 2005). This model poorly reflects the demands of team-sport games, where players are often required to perform multiple bouts of sprints (Spencer et al. 2004b). Therefore, the use of multiple sets of RSE allows a more accurate investigation of team-sport performance. To our knowledge, only three studies have investigated the multiple-set RSE by assessing the performance in response to an acute intervention (Beckett et al. 2009; Carr et al. 2008; Sim et al. 2009). However, all three studies measured only sprint time as their performance variable. Given the short duration of sprints during a match (Spencer et al. 2005), a key factor in team-sport performance is the ability of players to accelerate, rather than the ability to maintain a mean velocity. Further research is, therefore, required to assess changes in acceleration during multiple-set RSE, and to investigate the effects of training on performance and physiological responses.

Given the strong correlation between repeated-sprint ability and very high-intensity running/sprinting distance during a game (Rampinini et al. 2007), it is surprising that little attention has been directed towards the efficacy of sprint training to improve RSE performance. Sport-specific training and small-sided games (Buchheit et al. 2009; Hill-Haas et al. 2009; Spencer et al. 2004a), interval and continuous training (Bishop and Edge 2005; Buchheit et al. 2009; Buchheit et al. 2008; Edge et al. 2005; Ferrari Bravo et al. 2008; Glaister et al. 2007), and resistance training (Edge et al. 2006; Hill-Haas et al. 2007) have been investigated. However, only three studies to date have employed repeated-sprint training (Buchheit et al. 2008; Dawson et al. 1998; Ferrari Bravo et al. 2008). These studies described a 1–2.2% improvement in repeated-sprint ability, but only used mean/total sprint time to assess the performance. Repeated-sprint training differs from protocols utilising longer between-sprint recovery [e.g., 55 s; (Linossier et al. 1993)], or longer efforts [e.g., repeated all-out 30 s; (Gibala et al. 2006; McKenna et al. 1993)]. Further, these types of training do not reflect the specificity of team-sport performance. Therefore, we defined "repeated-sprint" as short sprints (<6 s) alternated with recoveries of less than 30 s. Also, laboratory cycling and outdoor running have been traditionally employed as RSE modalities. While cycle ergometry testing has limited applications to team sports, field-based sprinting can be difficult to control, and performance difficult to measure. Instead, non-motorised treadmills offer a suitable methodology to expand on previous research and to reliably assess performance in a standardised laboratory setting (Ross et al. 2009).

Therefore, the aims of the present study were (a) to comprehensively assess the performance and physiological characteristics of acute, multiple-set RSE on a non-motorised treadmill, (b) to investigate the effects of repeated-sprint training on RSE performance, and (c) to quantify relationships between $\dot{V}O_{2peak}$, intermittent running capacity, and indices of RSE performance.

Methods

Subjects

Ten healthy young adults (7 males, 3 females) gave written informed consent and participated in this study, which was approved by the Victoria University Human Research Ethics Committee and designed to conform to the Declaration of Helsinki. The baseline physical characteristics of the subjects were (mean ± SD): age 22.3 ± 4.1 years; height 174.4 ± 9 cm; mass 70.2 ± 11.6 kg. All participants were physically active and seven of them were involved in team sports at a recreational level.

Experimental overview

Prior to training, participants visited the laboratory on three separate occasions and performed an incremental exercise test on a treadmill, a Yo-Yo intermittent recovery test level 1 (Yo-Yo IR1), and a familiarisation trial of the repeated-sprint exercise (RSE); each test was separated by at least 48 h. After 2 weeks, all participants performed the pre-training RSE. Then, participants commenced their 10-session training programme (Monday, Wednesday, Friday), with each session consisting of a standardised warm up followed by a repeated-sprint protocol which replicated the pre-training RSE. Forty-eight hours after the last training session, the participants performed the post-training RSE. The incremental test and the Yo-Yo IR1 were then performed in this order and with each test separated by 48 h. Participants were asked to refrain from exercise, alcohol and caffeine consumption for 24 h before all tests.

Incremental test

This test was performed on a motorised treadmill (Quinton Q65, Seattle, WA, USA) and comprised 4-min exercise stages interspersed by 1 min of passive rest. The test commenced at a speed of 8 km h^{-1} for females and 9.1 km h^{-1} for males. The intensity was thereafter increased by 1.5 km h^{-1} every 4 min, with no gradient, until volitional exhaustion, defined as the subject's inability to maintain the running speed. Expired gases were analysed using a custom-made metabolic cart. Briefly, subjects breathed through a Hans-Rudolph 3-way non-rebreathing valve, with expired air passed through flexible tubing into a mixing chamber; expired volume was measured using a ventilometer (KL Engineering, Sunnyvale, CA, USA); mixed expired O_2 and CO_2 contents were analysed by rapidly responding gas analysers (S-3lA/II and CD-3A analysers, Ametek, PA, USA). The gas analysers were calibrated immediately prior to each test using commercially prepared gas mixtures (BOC, Australia). The ventilometer was calibrated prior to each test using a standard 3-L syringe. $\dot{V}O_{2peak}$ was calculated as the average of the two highest values in two consecutive 15-s periods. At rest, and immediately after the completion of each stage, a finger-tip capillary blood sample was collected from the participants while in a standing position, and analysed for lactate concentration ([Lac$^-$]) (Lactate Pro Analyser, Arkray Inc, Kyoto, Japan). The lactate threshold was calculated according to the two different methods, i.e. the intensity that precedes an increment of [Lac$^-$] of $\geq$1 mM (defined as "lactate threshold", LT), and the intensity corresponding to a fixed lactate concentration of 4 mM (defined as "onset of blood lactate accumulation", OBLA). Heart rate (HR) was recorded every second using a heart-rate monitor (RS800sd, Polar Electro Oy, Kempele, Finland). Ten minutes after the completion of the incremental test, subjects undertook an initial familiarisation on a non-motorised treadmill (Woodway Force, Waukesha, WI, USA), which comprised a 1-min walk, two 10-s runs (8 and 10 km h^{-1}) and one 4-s sprint. The purpose of this initial familiarisation was to habituate the participants to the non-motorised treadmill under a range of different exercise intensities.

Yo-Yo IR1

Forty-eight hours after the completion of the incremental test, the participants performed the Yo-Yo IR1, which is a field-based test that is broadly used in team sports to measure intermittent running capacity (Bangsbo et al. 2008). This test comprised 2 × 20-m shuttle runs at increasing speeds, separated by 10 s of active recovery. The participants were required to run on a parquet-floor indoor court, guided by a beep signal, until they were unable to maintain the desired speed. The test was terminated when the subjects were no longer able to reach the finish line on the beep signal on two consecutive occasions. The stage reached, along with the total distance covered (m), was recorded as the final result of the test. The reliability of the Yo-Yo IR1 in participants with a similar aerobic power to our subjects has been previously reported, with the coefficient of variation (CV) ranging from 4.9 to 8.7% (Krustrup et al. 2003; Thomas et al. 2006).

Familiarisation trial

At least 48 h after completing the Yo-Yo IR1, the participants reported to the laboratory to perform the main familiarisation session. The test began with a standardised warm up which consisted of 4 min of running on the motorised treadmill at a velocity corresponding to 60% of the velocity associated with $\dot{V}O_{2peak}$, followed by three runs on the non-motorised treadmill. In detail, the female participants performed two 4-s runs at 13 km h^{-1}, interspersed with 20 s of passive recovery, followed by 1 min of rest, before performing a final 4-s run at 15 km h^{-1}; males performed the same three 4-s runs at 15 and 17 km h^{-1}, respectively. After 1 min of passive recovery, the subjects were asked to complete two sets of 5 × 4-s maximal sprints separated by 20 s of passive recovery, with 4.5 min of active recovery between the sets. Participants completed only two sets of sprints in order to minimise the possibility of vasovagal episodes. For the same reason, participants were asked to slowly walk in the first 2 min of recovery. However, during the experimental RSE subjects were instructed to stand and limit movements, to closely replicate the pre- and post-training recovery conditions during which physiological responses (e.g., HR and blood [Lac$^-$]) were measured.

RSE

Two weeks following the familiarisation trial, the subjects performed the main RSE test. Participants initially undertook the above warm up protocol, with the exception that the three 4-s runs on the non-motorised treadmill were performed at 70 and 90% of the actual peak velocity reached during the familiarization trial. Participants were required, from a standing start, to reach as rapidly as possible the required velocity indicated on the treadmill, and to maintain that velocity for 4 s. The same warm up was subsequently used for all training sessions. The RSE commenced immediately (1 min) after the completion of the warm up, and consisted of three sets of 5 × 4-s sprints with 20 s of passive recovery between sprints and 4.5 min of passive rest between sets. During the RSE, mean and peak power, mean and peak velocity, and acceleration were measured. All measurements from the non-motorised treadmill were acquired with a sampling rate of 50 Hz, and the force transducers were calibrated before each trial according to the manufacturer's guidelines. The height of the horizontal force transducer was adjusted for each subject by measuring and reproducing the distance between the subject's anterior superior iliac spine and the belt of the treadmill, and maintained constant throughout the study. However, the imperfect horizontal position of the force transducer must be taken into consideration when interpreting results from the calculation of power (Morin et al. 2010). The mean HR during the 4.5-min recovery period was defined as the recovery HR and was measured as described above. In addition, two time domain measures of HR variability were calculated from the R-R intervals measured during the last 3 min of recovery with a HR monitor (RS800sd, Polar Electro Oy, Kempele, Finland). The calculation of the root-mean-square difference of successive normal R-R intervals (RMSSD), and the standard deviation of normal R-R intervals (SDNN) were applied to the last 3 min of data in order to evaluate the part of the recovery period that provided a more stationary HR. Finger-tip blood samples were collected at rest, immediately after sets 1 and 2, and 1 min after the last set, and were analysed for [Lac$^-$] (Lactate Pro Analyser, Arkray Inc, Kyoto, Japan). A Δ[Lac$^-$]-to-work ratio (Δ[Lac$^-$]/work) was calculated as the difference of [Lac$^-$] after each set and the baseline, and corrected for the total work performed [calculated from mean power and expressed as kiloJoules (kJ)]. This ratio allowed comparisons under conditions where the total work completed during RSE pre- and post-training was different. No correction for change in plasma volume was applied, as no statistically significant difference in plasma volume existed between RSE before and after training, for any of the three sets. Compared to rest, the change in plasma volume for sets 1, 2 and 3 was −17.7 ± 6.2, −17.7 ± 3.9, and −17.4 ± 5.1% before training, and −16.3 ± 2.8, −17.5 ± 3.8, and −19.4 ± 3.3% after training, respectively. A rating of perceived exertion was recorded immediately after the completion of the exercise using a 6–20 point scale [6 = very very light; 20 = very very hard (Borg 1982)]. Laboratory temperature and relative humidity during the trials were 21.8 ± 0.4°C and 37.0 ± 5.8%, respectively.

Calculation of measurements from the non-motorised treadmill

During the RSE, both visual and audio instructions (“3-2-1-Go”) were given to the participants by the same operator, in order to reduce the variability caused by differences in the sprint start. However, data analysis revealed an appreciable level of anticipation in each subject. To minimise the impact of this, the start point for the calculation of the sprints was defined as when a velocity of 1 m s^{-1} was attained; from then, a 4-s period was calculated.

Mean power and mean velocity were calculated as the average of all data sampled in the 4-s period. Peak power and peak velocity were determined as the highest single value recorded during a sprint. Preliminary analyses

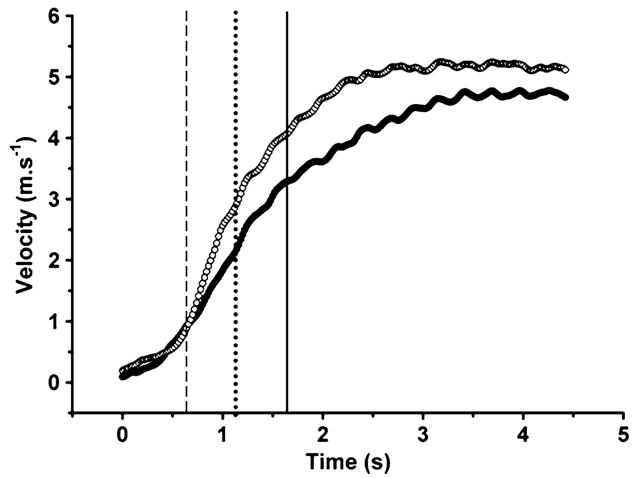

Fig. 1 Typical trend of the increase in velocity during a 4-s sprint, for the same participant, before (*filled circle*) and after (*open circle*) training. The *dashed line* represents the starting point for the 4-s calculations, which corresponded to the attainment of the 1 m s^{-1} velocity. The *dotted* and *solid lines* represent the conclusion of a 0.5-s and 1-s period, respectively

revealed no differences in peak power or velocity when the values were obtained from a single peak value or from an average of multiple peaks (2–5 highest values) recorded during the sprint. Acceleration was calculated as the rate of change in velocity in the 0.5 s immediately after attaining the 1 m s^{-1} velocity. This 0.5-s period was preferred to a 1-s period, as initial analysis demonstrated 0.5 s to better represent the maximal acceleration. That is, if velocity is measured during a 1-s period, a commencement of plateau in acceleration often occurs, therefore, failing to reflect maximal acceleration (Fig. 1).

Test–retest reliability and smallest worthwhile change

The pre-training RSE and the first training session (48 h apart) were used to determine the reliability of all performance measurements from the non-motorised treadmill, of the recovery HR, and of the HR variability (i.e., RMSSD and SDNN). Calculations of reliability allow a more correct interpretation of the results in a single-group, pre-post research design, with similar information to those provided by the use of a control group. Reliability was calculated as typical error expressed as a CV (Hopkins 2000). The CV was 4.7 and 10.8% for mean and peak power; 2.6 and 3.5% for mean and peak velocity; 7.6% for acceleration, 7.3% for recovery HR, and 19.3 and 23.9% for SDNN and RMSSD, respectively. The same data sets were used to calculate the smallest worthwhile change, which was estimated as 0.2 × between-subject standard deviation expressed as a CV (%) (Batterham and Hopkins 2006). The smallest worthwhile change was 5.7 and 7.5% for mean and peak power, 2.8 and 2.7% for mean and peak velocity, 5.7% for acceleration, 3.8% for recovery HR, and 10.9 and 12.8% for SDNN and RMSSD.

Statistical analysis

Data are expressed as mean ± SD. Results were tested for normal distribution using a Shapiro–Wilk W test. All data met the assumption of normal distribution ($p > 0.05$) with the exception of SDNN and RMSSD. A log transformation was applied to these two measures in order to reduce bias due to the non-uniformity of error. Then, performance and physiological responses to RSE were analysed using a two-way ANOVA with repeated measures, with Bonferroni post hoc tests. Results from the incremental test and the Yo-Yo IR1 were analysed using a paired t test. Statistical significance was set at $p < 0.05$. Pearson product moment correlation coefficient was used to examine the relationships between the indices of RSE performance, $\dot{V}O_{2peak}$, Yo-Yo IR1 performance and physiological responses. The magnitude of the changes was assessed using effect size (ES) statistic with 90% confidence intervals (CI) and percentage change (Batterham and Hopkins 2006; Hopkins 2007). ES were classified as follows: <0.2 = trivial, 0.2–0.6 = small, 0.6–1.2 = moderate, 1.2–2.0 large, >2.0 = very large (Hopkins 2003).

Results

RSE performance

Before training, performance progressively decreased across the three sets of acute RSE, with a reduction in the majority of the indices in set 3 versus set 1 (Table 1). Mean power decreased by 4.8% in set 3 versus set 1 ($p = 0.006$, ES = −0.21 ± 0.07), peak power was reduced by 9.2% ($p = 0.027$, ES = −0.28 ± 0.11), and mean velocity declined by 2.2% ($p = 0.019$, ES = −0.18 ± 0.33). Ten sessions of repeated-sprint training produced improvements in all measurements except for peak power, with changes between 5 and 10%, and small to moderate effects (Table 1). During the post-training RSE, mean power in set 3 was 4.1% lower than set 1 ($p = 0.006$, ES = −0.19 ± 0.06), and mean velocity was reduced by 2.1% ($p = 0.014$, ES = −0.17 ± 0.06), hence similar to the pre-training decrements. The reduction in peak power after training in set 3 was unclear ($p = 0.051$, ES = −0.19 ± 0.10).

Before training, there was no difference in the acceleration between sets. After training, acceleration was substantially improved, being 21.9, 14.7 and 15.2% greater than pre-training values for set 1, 2, and 3, respectively; ES were 0.81 ± 0.16, 0.60 ± 0.18 and 0.63 ± 0.22, respectively. During the post-training RSE, acceleration in set 3 was 6.9% less than that recorded in set 1 ($p = 0.010$; ES = −0.32 ± 0.33; Fig. 2).

Physiological responses to acute and chronic RSE

Capillary blood [Lac$^-$] did not change between pre- and post-training RSE, being 1.2 ± 0.3 versus 1.4 ± 0.4 mM at rest, 9.1 ± 2.1 versus 8.8 ± 2.6 mM after set 1, 11.5 ± 2.6 versus 11.5 ± 3.0 mM after set 2, and 12.3 ± 2.8 versus 12.6 ± 3.2 mM after set 3. However, due to the increase in the total work performed, the Δ[Lac$^-$]/work after training was lower compared to pre-training at all time points (Fig. 3).

Table 1 Summary of changes in RSE performance before and after repeated-sprint training ($n = 10$)

	Set #	Pre-training	Post-training	% change	ES ± 90% CI
Mean power (W)	1	734 ± 172	800 ± 188§	8.8	0.38 ± 0.08
	2	720 ± 161	787 ± 177§	9.2	0.41 ± 0.07
	3	698 ± 165*	764 ± 167*, §	9.6	0.39 ± 0.08
Peak power (W)	1	2,096 ± 622	2,276 ± 864	6.2	0.29 ± 0.17
	2	2,036 ± 650	2,180 ± 724	6.7	0.22 ± 0.14
	3	1,916 ± 624*	2,113 ± 628	10.7	0.31 ± 0.13
Mean velocity (m s^{-1})	1	4.10 ± 0.53	4.42 ± 0.57§	7.7	0.59 ± 0.10
	2	4.08 ± 0.50	4.37 ± 0.55§	7.2	0.59 ± 0.09
	3	4.01 ± 0.51*	4.32 ± 0.52*, §	7.8	0.60 ± 0.11
Peak velocity (m s^{-1})	1	4.98 ± 0.62	5.25 ± 0.63§	5.5	0.44 ± 0.10
	2	4.92 ± 0.60	5.23 ± 0.66§	6.2	0.50 ± 0.11
	3	4.90 ± 0.57	5.18 ± 0.62§	5.6	0.48 ± 0.14

RSE consisted of three sets of 5 × 4-s maximal sprints on a non-motorised treadmill

* Significantly less than set 1 ($p < 0.05$)

§ Significantly greater than pre-training ($p < 0.05$)

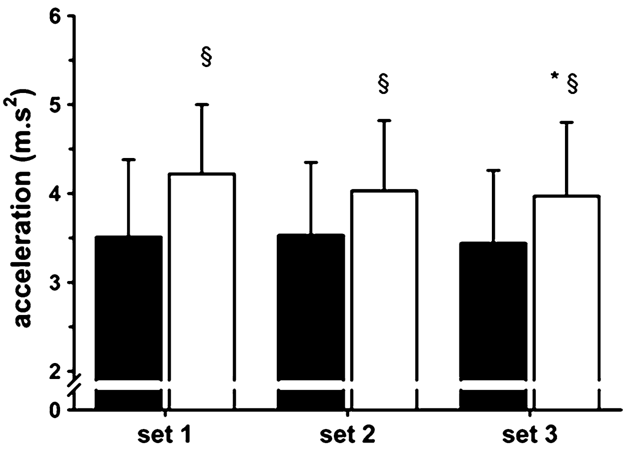

Fig. 2 Effects of training on acceleration during acute RSE ($n = 10$). *Significantly less than set 1 ($p < 0.05$); §Significantly greater than pre-training ($p < 0.05$); *filled bars* pre-training; *open bars* post-training

Percent change and ES post-training versus pre-training were −15.2% and −0.60 ± 0.44 for set 1; −12.7% and −0.50 ± 0.32 for set 2; −9.4% and −0.74 ± 0.52 for set 3, respectively.

Before training, average HR during the 4.5 min recovery period following sets 1, 2, and 3 was 136 ± 9, 138 ± 9 and 138 ± 7 beats min^{-1}, respectively, and did not differ between sets ($n = 8$, due to technical problems with HR monitoring). After the training intervention, recovery HR decreased in all three sets, being 125 ± 11 (−8%, $p < 0.001$, ES = −1.03 ± 0.37), 132 ± 8 (−4.2%, $p = 0.001$, ES = −0.55 ± 0.23) and 135 ± 8 beats min^{-1} (−2.7%, $p = 0.024$, ES = −0.49 ± 0.26) for sets 1, 2 and 3, respectively. During the post-training RSE, the average recovery HR increased after set 2 and 3, compared to set 1. Before training, SDNN was 36.4 ± 14.5, 30.9 ± 12.4, and 26.7 ± 8.0 ms ($p = 0.050$ set 3 vs. set 1), and RMSSD was 6.1 ± 2.4, 5.7 ± 3.4, and 5.3 ± 3.7 ms, after set 1, 2 and 3, respectively ($n = 7$). Post-training, SDNN increased by 22.3% after set 1 ($p = 0.085$, ES = 0.50 ± 0.56), 16.7% after set 2 ($p = 0.179$, ES = 0.37 ± 0.53), and 46.3% after set 3 ($p = 0.003$, ES = 1.06 ± 0.54). RMSDD increased by 53.3% ($p = 0.005$, ES = 0.90 ± 0.71) and 12% ($p = 0.399$, ES = 0.20 ± 0.30) after set 1 and 2, respectively, but decreased by −3.9% after set 3 ($p = 0.762$, ES = −0.07 ± 0.40). Rating of perceived exertion measured immediately after exercise did not show any change, being 16.8 ± 2.4 post-training versus 16.7 ± 2.3 pre-training ($n = 10$).

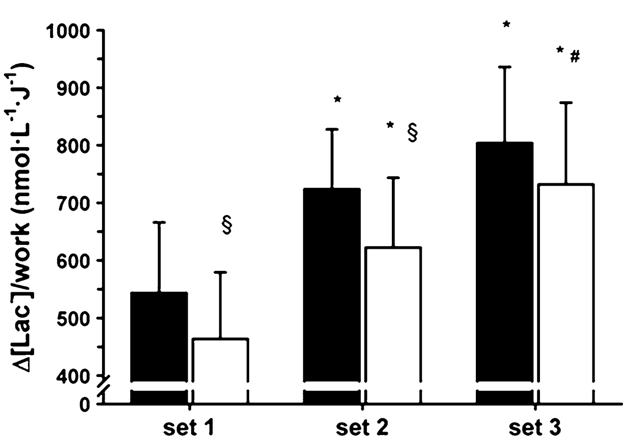

Fig. 3 Δ[Lac⁻]/work ratio during acute RSE before and after training ($n = 10$); *significantly greater than set 1 ($p < 0.05$); #significantly greater than set 2 ($p < 0.05$); §significantly less than pre-training ($p < 0.05$); *filled bars* pre-training; *open bars* post-training

Yo-Yo IR1, $\dot{V}O_{2peak}$ and lactate threshold

Pre-training Yo-Yo IR1 performance was 1,305 ± 709 m and increased after training by 8% to 1,400 ± 715 m ($p = 0.021$, ES = 0.12 ± 0.08; $n = 8$). Absolute $\dot{V}O_{2peak}$ before training was 3.79 ± 0.63 L min^{-1} and did not differ after training, being 3.86 ± 0.70 L min^{-1} ($p = 0.223$, ES = 0.16 ± 0.11). Relative $\dot{V}O_{2peak}$ was 53.7 ± 6.9 and 54.8 ± 6.6 mL kg^{-1} min^{-1} pre- and post-training, respectively ($p = 0.074$, ES = 0.18 ± 0.13). There were no changes in the LT and OBLA. LT was 11.4 ± 2 km h^{-1} before training, corresponding to 70.5 ± 9.4% of the velocity associated with $\dot{V}O_{2peak}$, and 11.0 ± 1.7 km h^{-1} after training (−3.3%, $p = 0.34$, ES = −0.18 ± 0.34). OBLA before training was 12.4 ± 1.8 km h^{-1} and corresponded to 76.5 ± 6% of the velocity associated with $\dot{V}O_{2peak}$; after training, OBLA was 12.4 ± 1.8 km h^{-1} with a 0.7% change ($p = 0.57$, ES = 0.04 ± 0.13).

Relationships between Yo-Yo IR1, $\dot{V}O_{2peak}$ and RSE performance

A summary of the relationships between the indices of RSE performance, the $\dot{V}O_{2peak}$ and Yo-Yo IR1 is provided in Table 2. There were large significant correlations between Yo-Yo IR1 and RSE performance, with a very large correlation between Yo-Yo IR1 and acceleration after training. There were weak non-significant relationships between $\dot{V}O_{2peak}$ and indicators of RSE, except for acceleration and mean velocity after training. There were very large correlations between $\dot{V}O_{2peak}$ and Yo-Yo IR1 performance before ($r = 0.87$, $p = 0.012$) and after training ($r = 0.90$, $p = 0.006$), but a non-significant correlation between the percent changes in the two measures after training ($r = 0.56$, $p = 0.191$). There were no significant correlations between RSE performance and LT or OBLA.

Table 2 Summary of the relationships between measures of aerobic power and indices of RSE performance before and after training

	Acceleration (m s^{2})		Mean power (W)		Peak power (W)		Mean velocity (m s^{-1})		Peak velocity (m s^{-1})	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Yo-Yo IR1 (m)	0.61	0.88*	0.75*	0.82*	0.73*	0.73*	0.74*	0.86*	0.77*	0.83*
$\dot{V}O_{2peak}$ (mL kg^{-1} min^{-1})	0.35	0.71*	0.45	0.62	0.48	0.61	0.45	0.67*	0.49	0.63

$n = 8$ for Yo-Yo IR1; $n = 9$ for $\dot{V}O_{2peak}$

Relationships are expressed as a Pearson product moment correlation coefficient (r)

* Statistically significant ($p < 0.05$)

Discussion

There were three main findings in the present study. Firstly, ten sessions of repeated-sprint training, comprising a total of only 10 min of exercise, induced (a) a moderate, practically important improvement in acceleration, (b) an improvement in indices of RSE performance, Δ[Lac^{-}]/work and recovery HR, and (c) an increase in the intermittent running capacity, despite no changes in the $\dot{V}O_{2peak}$, the LT or OBLA. Secondly, there were strong correlations between Yo-Yo IR1 performance and indices of RSE performance. Finally, performance during multiple sets of RSE progressively decreased from set 1 to set 3, with peak power reporting the biggest decrement pre-training, and acceleration being most affected after training.

Training improves acceleration during multiple-set RSE

To our knowledge, this is the first study to quantify the training-induced improvements in the capacity to accelerate. A conventional method to assess the acceleration during a sprint is to record the time or the average velocity over the initial 5 or 10 m (Harrison and Bourke 2009; Spinks et al. 2007). However, despite acceleration being the main component in the initial phase of a sprint, these indirect measurements do not provide information on the rate of change of the instantaneous velocity during the sprint. Instead, using a non-motorised treadmill, we detected the actual change in acceleration during RSE. Such a change was two to three times greater than the CV, and three to four times greater than the smallest worthwhile change calculated before training; therefore, this enhancement in acceleration was genuine and can be attributed to the training intervention.

The mechanisms underlying the improvement in acceleration after training might include an increase in power output and reactive strength at the beginning of the sprints, possibly via improved neuromuscular adaptations (e.g., change in fibre recruitment pattern). In support of this, 8 weeks of repeated-sprint training has previously been reported to produce an increase in both the velocity over 15-m sprints and countermovement jump height, without any significant changes in lower-body kinematic variables and stride length/frequency in the first two steps (Spinks et al. 2007). Amongst all indices of RSE performance, acceleration returned the largest improvement, which was up to four times greater than the change in peak velocity. This highlights the importance of including a measure of acceleration in match analysis, RSE testing, and training studies that investigate sport-specific sprint performance. For example, traditional analysis of high-intensity activity, taking only high-velocity running into account, ignores the physically demanding nature of accelerations (Osgnach et al. 2010) and, therefore, underestimates the real amount of high-intensity activity (Little and Williams 2007). By directly measuring acceleration, one cannot only gain a deeper understanding of the components of repeated-sprint performance in a controlled laboratory environment, but also a more complete interpretation of the real demands of the task. This ultimately allows a better targeting of subsequent training interventions.

Indices of repeated-sprint ability

Multiple sets of repeated sprints induced a significant reduction in performance during set 3 compared to set 1. This is in line with previous research showing a significant reduction of mean/total sprint time after the third set (approximately −1.2%) when between-set passive recovery was performed (Beckett et al. 2009). The results of the present study also suggest that peak power is affected to a greater extent than mean power or velocity during multiple-set RSE before training. However, after the training intervention it was the capacity to accelerate that reported the largest decrement (−6.9%, ES = −0.32 ± 0.33) in set 3 versus set 1. The training-induced enhancement in acceleration was accompanied by small-moderate improvements in mean power/velocity and peak velocity, and a small-trivial change in peak power. Interestingly, the improvements in these indices were greater than those measured in the three previous studies which employed repeated-sprint training (Buchheit et al. 2008; Dawson et al. 1998; Ferrari Bravo et al. 2008). Firstly, the lower values of $\dot{V}O_{2peak}$ of the participants in this study, which may reflect a lower training status, could partly explain the greater changes in RSE performance. In addition, the use of a non-motorised treadmill might have produced, concomitant with the training adaptations, a learning effect which is not present in field-based sprinting. As the participants of this study had to run on a non-motorised treadmill wearing a belt that was connected to a force transducer, this may also represent a small resistance that requires additional work to perform, similar to what occurs during resisted sprinting (Harrison and Bourke 2009; Spinks et al. 2007). Ultimately, it is interesting to note that in the present study the training intervention consisted of only ten sessions, while previous studies employed from 14 to 18 sessions distributed over 6–9 weeks (Buchheit et al. 2008; Dawson et al. 1998; Ferrari Bravo et al. 2008). However, in one study it has been observed that repeated-sprint ability improves during the first weeks of interval training, reaching a peak at the fourth week, followed by a plateau in the following weeks despite an increase in the training load (Bishop and Edge 2005). Thus, it is possible that the ten sessions of training employed in this study were optimal to elicit peak changes in RSE performance. Nonetheless, further research is required to understand if a plateau in RSE performance also occurs with repeated-sprint training. Verification of our observation that repeated-sprint training interventions produce positive adaptations in a limited amount of time, would provide essential information on how to optimally train this important fitness component for team-sports.

Training reduces $\Delta[Lac^-]$/work and recovery HR

Ten sessions of repeated-sprint training produced a reduction in $\Delta[Lac^-]$/work measured during acute RSE. This could be explained through a greater participation of the aerobic system during RSE, an increased production and/or clearance of lactate (Stallknecht et al. 1998), or possibly an increase in blood volume. A greater aerobic ATP contribution during RSE might have supported the increase in work despite an unchanged $[Lac^-]$. Six sessions of repeated, all-out exercise bouts improved oxygen uptake and muscle deoxygenation kinetics during exercise at two constant intensities, with a concomitant reduction of the blood $[Lac^-]$; this was not detected after continuous training performed at a lower intensity (Bailey et al. 2009). The lower $\Delta[Lac^-]$/work after training might also reflect a greater lactate clearance during exercise. One of the mechanisms responsible for this is the action of the monocarboxylate transporters (MCT), which transport lactate across the muscle cell and mitochondrial membrane. Skeletal muscle MCT1 and MCT4 protein abundance increased after a training intervention involving multiple 6-s sprints interspersed with 1 min of recovery (Mohr et al. 2007). It is likely that both an improved oxidative metabolism and an enhanced lactate clearance contributed to the reduction in the $\Delta[Lac^-]$/work after training in the present study.

Ten sessions of training also reduced recovery HR during acute RSE. This might be explained through an improvement in autonomic control, either via increased parasympathetic function or sympathetic withdrawal, during the recovery following the three sets of RSE. The improvements in markers of HR variability support the idea of an enhanced autonomic control, in particular after the first set of sprints. Similar to our results, 9 weeks of repeated-sprint training improved indices of HR recovery from ~5 to 13%, with a 52% increase in RMSSD and a 13% increase in SDNN, following a 6-min exercise at a constant intensity (Buchheit et al. 2008). In addition, the training-induced changes in HR recovery were positively correlated ($r = 0.62$) with the improvements in repeated-sprint ability (Buchheit et al. 2008), linking a practical measure of recovery to performance during short, all-out exercise. Likewise, in our study we found a large positive correlation between the training-induced decrement in recovery HR after set 1, and the increase in mean power during set 2 ($r = 0.81$, $p = 0.016$). Further research is required to elucidate the mechanisms underlying an improved HR recovery and variability after repeated-sprint training, and to investigate whether a causal relationship exists between an enhanced recovery after one set of sprints and the performance during the subsequent set.

RSE performance and Yo-Yo IR1 performance are strongly correlated

One of the focal points of research investigating RSE has been an attempt to understand the extent to which different physical capacities determine performance, with a particular interest in aerobic power. It is well accepted that maximal oxygen uptake might not be the most important determinant of repeated-sprint ability, and this is supported by the moderate correlations that have been found between these two parameters (Aziz et al. 2000; Bishop et al. 2004). However, it was of interest to see whether aerobic power might be correlated with RSE performance when participants were asked to complete multiple sets of sprints. The results from the present study indicate no significant correlations between $\dot{V}O_{2peak}$ and any of the indices of RSE performance ($r = 0.45$–0.61, $p > 0.05$). After training, all correlations became stronger, but only those with mean velocity and acceleration reached statistical significance. No correlation was present between the training-induced changes in $\dot{V}O_{2peak}$ and the improvement in acceleration or velocity. Conversely, we found large correlations between Yo-Yo IR1 performance and RSE performance before training, and even larger correlations after training (Table 2). Importantly, acceleration during pre-training RSE was the physical capacity that had the poorest correlation with Yo-Yo IR1 performance ($r = 0.61$, $p = 0.109$), but the strongest correlation after training ($r = 0.88$, $p = 0.004$). This may be explained by the fact that both types of exercise require repeated accelerations with short recovery between repetitions, and repeated-sprint training might have created specific adaptations which are important for intermittent running performance.

Conclusions

Ten sessions of repeated-sprint training were effective in improving acceleration, repeated-sprint ability, and intermittent running capacity in young healthy adults. This repeated-sprint intervention had a remarkably low training volume, with a total of only 10 min of exercise (140 min including recovery periods). This is, therefore, a time-efficient intervention that can be integrated into the training programmes of many intermittent sports. Further, low-volume, all-out training can improve specific components important for team-sport performance, in particular acceleration, without inducing a concomitant decrement in the maximal aerobic power. This is of great practical application in the modern sport environment, where the competition calendar limits the time that can be dedicated to training. In addition, this study adds important information on the extent to which the different indices of repeated-sprint ability are involved in the decline of performance across multiple sets of sprints. This type of exercise more closely resembles the activity profile of team sports and might be more appropriate than a traditional single-set test to evaluate repeated-sprint ability in intermittent sport activities. Furthermore, this study is in line with the increasing interest towards short-term, all-out exercise programs to improve sport performance and health-related indices (Benziane et al. 2008; Burgomaster et al. 2008; Thomassen et al. 2010).

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