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ORIGINAL ARTICLE

Physiological and performance responses of sprint interval training and endurance training in Gaelic football players

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Abstract

Purpose While ideal for developing aerobic capacity, traditional endurance training (ET) is extremely time-consuming and may lack the specificity to maintain indices of speed and power in team sport athletes. In contrast, low-volume short-duration sprint interval training (SIT) has been shown to improve $\dot{V}O_2$max to a similar extent as ET. However, to date, few studies have compared the effects of running-based SIT and ET, on aerobic capacity and indices of speed and power of trained team sport athletes.

Methods Club level male Gaelic football players were randomly assigned to SIT ($n = 13$; 26.5 ± 4.87 years) or ET ($n = 12$; 25.4 ± 2.58 years) groups. Participants trained 3 days week^{-1} for 6 weeks. $\dot{V}O_2$max, RE, v$\dot{V}O_2$max, blood lactate concentrations, Wingate test performance, running speed, jump performance and intermittent endurance performance (IEP) were measured at baseline and after 6 weeks.

Results An increase in $\dot{V}O_2$max ($p < 0.05$), v$\dot{V}O_2$max ($p < 0.001$) and IEP ($p < 0.001$) following 6 weeks of both SIT and ET was observed. Wingate mean power ($p < 0.001$), peak power ($p < 0.001$) and fatigue index ($p < 0.005$) were all significantly improved following training in both groups. Velocity at LT was significantly higher and performance in the 20-m running speed and VJ tests were significantly reduced post training in the ET group (all $p < 0.005$).

Conclusion Despite the large difference in total training time, a running-based protocol of SIT is a time efficient training method for improving aerobic capacity and IEP while maintaining indices of lower body power and running speed in team-sport players.

Keywords Team sport · Maximal oxygen uptake · Speed · Power · Running

Abbreviations

BMI	Body mass index
CMJ	Counter-movement jump
COX	Cytochrome c oxidase
CPET	Cardio-pulmonary exercise test
ET	Endurance training
FI	Fatigue index
H^+	Hydrogen ion
HR	Heart rate
HRmax	Maximal heart rate
IEP	Intermittent endurance performance
LT	Lactate threshold
MCT	Monocarboxylate transporter
MP	Mean power
PAR-Q	Physical activity readiness questionnaire
PCr	Phosphocreatine
PP	Peak power
RE	Running economy
RPE	Rate of perceived exertion
SD	Standard deviation
SIT	Sprint interval training
VEmax	Maximal ventilation
VJ	Vertical jump
VO_2	Oxygen uptake

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$\dot{V}O_2max$	Maximal aerobic capacity
$v\dot{V}O_2max$	Velocity at maximal oxygen uptake

Introduction

Gaelic football is a field-based invasion team sport characterized by irregular changes of pace and anaerobic efforts interspersed with periods of light to moderate aerobic activity. Sub-elite club level players cover approximately 7.0 km during a game (Mangan et al. 2020), the majority of which is spent at low to moderate intensity and, therefore, requires significant aerobic energy system contribution. However, many of the important events during match play involve single or repeated short-duration bouts of activity lasting ~ 3–6 s, involving high running velocities (6.5–7.5 m s^{-1}) and muscle power (Reilly and Collins 2008). These high-intensity activities rely on the phosphagen system and anaerobic glycolysis with their relative contribution dependent, in large part, on the intensity and duration of the activity and recovery intervals. Since PCr resynthesis occurs primarily by oxidative processes, a high maximal aerobic capacity ($\dot{V}O_2max$) enhances the replenishment of phosphagen stores, during single and repeated bouts of high-intensity activity (McMahon and Jenkins 2002) and has been shown to contribute to a higher playing intensity and greater engagement with play (Helgerud et al. 2001). In addition, the ability to apply high levels of force rapidly impacts a players ability to generate high-power outputs (Kawamori and Haff 2004) and is a well-developed fitness attribute in many invasion team sports (Pyne et al. 2005; Gabbett et al. 2009).

High volume endurance training (ET), a form of training that involves continuous running undertaken at low to moderate intensities has been traditionally used to improve physical performance in club level Gaelic football players. A large number of laboratory-based studies have found that 1–6 months of ET results in significant improvements in $\dot{V}O_2max$ and endurance performance (Milanović et al. 2015). While ET can develop aerobic capacity, it is time-consuming and may lack the specificity required to develop or maintain running speed and muscle power (Hennessy and Watson 1994).

Sprint interval training (SIT) involves repeated short-duration bouts (≤ 30 s) of maximum intensity (all out) exercise interspersed with periods of passive recovery (1–4 min) (Buchheit and Laursen 2013b). Compared to ET (~ 40–80 min per session), this type of training is less time-consuming (~ 5–40 min, 10–15% of which is active exercise) and allows players to undertake a greater volume of high-intensity activities (Burgomaster et al. 2008; Buchheit and Laursen 2013a) while eliciting similar physiological and metabolic adaptations (Rowan et al. 2012; Cocks et al. 2013; Macpherson and Weston 2015; Purkhús et al. 2016). Given the markedly lower training volume involved with SIT, this form of training may be used as a potential time-efficient strategy to increase $\dot{V}O_2max$ and endurance performance. Furthermore, a greater transfer to on-field performance may be possible if training activities involve similar motor patterns, contraction types, and force patterns as used during competitive performance activity (Young 2006). In addition, SIT may be more effective than ET at developing/maintaining additional components of fitness important for field-based team sport such as running speed and power (Buchheit and Laursen 2013a).

The present study sought to further investigate and extend the findings from previous work in our lab showing a significant increase in $\dot{V}O_2max$ after only 2 weeks of SIT (Kelly et al. 2018). Our initial study was limited by a short training period (2 weeks) and it could be argued that the very intense nature of SIT might stimulate rapid skeletal muscle remodelling, whereas adaptations to lower intensity ET may occur more slowly (Burgomaster et al. 2008). In addition, previous research has focused on the effect of SIT and ET on cardiorespiratory fitness and endurance performance while neglecting to investigate its impact on other key components of sport-related fitness such as running speed and power. Surprisingly, no studies to date have compared running speed of trained adults following both SIT and ET, while limited studies have assessed lower body power (Gibala et al. 2006; Burgomaster et al. 2008). Furthermore, methods used to assess lower body power (30 s Wingate anaerobic performance test) and the training mode (cycling) utilised in previous studies may have lacked the specificity to adequately assess this key component of fitness required for optimal performance in field-based invasion team sport. The aim of the present study was to compare the effect of 6 weeks of SIT and ET on physiological, metabolic and performance parameters of athletes involved in a field-based invasion team sport.

Methods

Experimental design and participants

Twenty-five adult club level Gaelic football players (mean ± SD; age 25.9 ± 3.8 years; BMI 24.5 ± 2.2 kg m^2; $\dot{V}O_2max$ 52.7 ± 5.4 ml min^{-1} kg^{-1}) participated in the study prior to the competitive phase of the season. Each player had a minimum of 3 years' playing experience at senior club level Gaelic football. During the season participants undertook two field-based training session per week, played a competitive game on most weekends and supplemented their field-based activity with at least one weekly resistance training session. Participants were older than 18 years of age, were members of a senior club panel and at the time

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of data collection were injury- and illness free. Participants were fully informed of the experimental procedures and possible discomforts associated with the study before providing written informed consent. The study was approved by the Dublin City University Research Ethics Committee (DCUREC 164).

A random number generator was used to randomly assign participants to either a ET or SIT group. Following allocation, participants in both groups undertook 18 sessions over a 6-week period, with assessment of physiological, metabolic and performance parameters before and after training. The intervention replaced all training and participants were instructed to refrain from any additional strenuous physical activity (individual and/or team training) for the duration of the study. They were also instructed to continue their normal dietary practices throughout the study but refrain from alcohol and caffeine for 24 h prior to each laboratory visit for assessment.

Pre-experimental procedures

Prior to baseline testing, participants attended the laboratory for an information and familiarization session in order to become oriented with the testing procedures and training protocols. This was carried out to ensure that any learning effect was minimal for the baseline testing assessments. Participants made three further visits to the Human Performance Laboratory with each visit separated by 48 h. During the first visit, participants completed a physical activity readiness (PAR-Q) and general health questionnaire. Height and body mass were measured to the nearest 0.1 cm and 0.1 kg, respectively, using a portable scale (Seca 707 Balance Scales, GmbH, Hamburg, Germany). Participants were instructed to wear a light top and shorts and to remove their shoes prior to the measurement.

Body mass index (BMI) was calculated as body mass (kg) divided by body height in square meters. Skinfold measurements were taken from the right side of the body using a Harpenden calipers (British Indicators, Hertfordshire, United Kingdom) and recorded to the nearest 0.2 mm by the lead investigator. Measurements included the following seven skinfold sites: triceps, subscapular, biceps, iliac crest, supraspinale, abdominal, mid-thigh. Pilot testing was used to verify the accuracy of the anthropometrical measurements performed (Hume and Marfell-Jones 2008). When intra-rater reliability was assessed for skinfolds, the technical error of measurement of three repeated trials was lower than 5% in line with recommendations (Hume and Marfell-Jones 2008; Stewart et al. 2011). The median of triplicate measurements was used for all subsequent analysis. All measurements were taken following the guidelines outlined by the International Society for the Advancement of Kinanthropometry (Stewart et al. 2011). Sum of skinfolds was calculated by adding all seven sites (listed above) together and percentage body fat was calculated according to the equations previously described by Jackson and Pollock (1978).

Following anthropometric assessment, participants performed a Wingate Anaerobic performance test on a Monark 894E cycle ergometer (Monark, Varberg, Sweden). The ergometer was calibrated prior to each test. The test was preceded by a 5-min warm-up at a self-regulated intensity against zero resistance. Following a 5-s countdown a resistance equal to 7.5% body mass was applied and the participant exercised maximally for 10 s. A 6 × 10 s Wingate test protocol (Zajac et al. 1999) was selected with each 10 s effort separated by 50 s of self-regulated active recovery. Verbal encouragement was given throughout each trial. Following completion of the test, participants continued cycling against zero resistance for 2–3 min to assist recovery. Peak power (PP), mean power (MP) and fatigue index (FI) were measured over the six trials. PP was defined as the maximum power exerted during a 5-s period of the test. MP was defined as the average power exerted during the 10-s work bout (average across six trials) and FI as the average power drop off (peak—minimum power) during the 10-s test (average across six trials).

During the second visit, participants' jump performance (height) and running speed (s) were assessed after which they undertook a cardio-pulmonary exercise test (CPET). Vertical jump (VJ) and counter movement jump (CMJ) tests were performed on a FSL JumpMat (FSL, Cookstown, Ireland). SMARTSPEED wireless electronic timing gates (Fusion Sport International) were used to measure 5 m and 20 m running times. Participants' jump performance and running speed were assessed over three trials with the best score reported for analysis.

The CPET involved participants warming-up at 8 km h^{-1} for 3 min at 1% gradient, after which the treadmill velocity was increased by 1.0 km h^{-1} every 3 min. At the end of each 3-min stage, participants straddled the moving treadmill and a 5-µl blood sample was taken from the earlobe to determine whole blood lactate concentration. When blood lactate concentration reached 4 mmol l^{-1}, the treadmill velocity was then kept constant and the gradient increased by 1% every 60 s until the participant reached volitional fatigue. $\dot{V}O_2$max was deemed successfully attained if the test satisfied at least three of the following criteria: plateaux in oxygen consumption despite increases in external work, RPE > 18, RER > 1.1 and heart rate above 95% of the age predicted max. Running Economy (RE) was examined in ml kg^{-1} min^{-1}, ml kg^{-1} km^{-1} and kcal kg^{-1} km^{-1} at submaximal speeds of 8, 9, 10 and 11 km h^{-1}. The predicted treadmill velocity at $\dot{V}O_2$max (v$\dot{V}O_2$max) was determined by extrapolating from the sub-maximal velocity-$\dot{V}O_2$ relation during the CPET. Heart rate (HR) was monitored at 5-s intervals during the exercise (Polar S610 monitor, Kempele, Finland),

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and HRmax was determined as the highest 5-s mean value. The rating of perceived exertion (RPE) was obtained using the 6–20 category Borg RPE scale (Borg 1998) which was explained in full to participants (written and verbal instruction) during the familiarization session. HR and RPE were both recorded during the final 10 s of each stage.

A test of intermittent endurance performance (IEP) was performed during the third laboratory visit which took place at least 48 h after completion of the CPET. Following a 3-min warm-up at 50% $v\dot{V}O_2max$, participants ran at 75% $v\dot{V}O_2max$ for 20 min after which they performed a series of alternating 1-min bouts of high-intensity running at 100% $v\dot{V}O_2max$ interspersed with 1-min bouts of moderate intensity at 75% $v\dot{V}O_2max$ until volitional fatigue.

After completing the training protocol, participants performed the same physiological assessments, starting with the assessment of anthropometric characteristics and Wingate performance (48 h after the last training session).

Training intervention

Participants commenced the training protocol 48 h following the final pre-training assessment visit. Training involved three sessions of SIT or ET per week on alternate days (i.e., Monday, Wednesday, Friday) for 6 weeks. Endurance training consisted of 40–50 min of continuous treadmill running at a velocity corresponding to 75% $v\dot{V}O_2max$. During the first 2 weeks, participants ran continuously on a treadmill (Woodway ELG 55, Waukesha, WI) for 40 min at 75% $v\dot{V}O_2max$. The duration was increased to 50 min at the beginning of week 3 and remained constant thereafter.

The SIT protocol involved 3–4 sets of maximum intensity running interspersed with short inter-set and long intra-set recovery periods. Participants sprinted 100 m with a change of direction at 50 m (Fig. 1). Each sprint was followed by a 25-m walk/jog recovery with a change of direction at 12.5 m. Each sprint repetition and recovery period was 40 s in duration. On average, participants completed the 100-m sprint in 17–20 s, allowing for a 20–23 s inter-set recovery period. A single set was comprised of 4 × 100 m sprints. Each set was followed by a 3-min intra-set recovery period. Participants completed 3 sets (12 sprints) during the training sessions in weeks 1 and 2, and the number of sets was increased to 4 (16 sprints) for the remaining 4 weeks of the study.

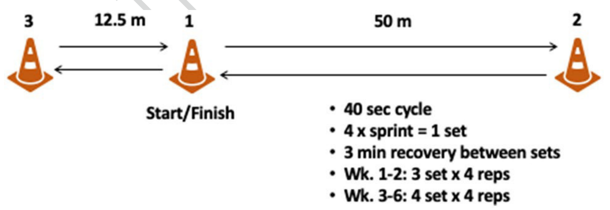

Fig. 1 Schematic of the SIT running protocol. Each interval run was 100 m in total sprinting distance and included one 180 degree turn at 50 m. A set consisted of 4 × 100 runs on a 40 s cycle. Training sessions in weeks 1 and 2 consisted of 3 sets and sessions in weeks 3, 4, 5 and 6 consisted of 4 sets. A 3-min recovery period was included between sets

Participants performed a 10-min self-selected warm-up prior to each training session that included aerobic running, dynamic stretches and higher intensity intervals. All training sessions for both groups were supervised by one of the study investigators and participants were verbally encouraged throughout both exercise protocols.

Lactate analysis

Blood samples were drawn from the earlobe and measured for lactate. Prior to each sample, the earlobe was wiped with alcohol and allowed to dry thoroughly. The base of the earlobe was pierced with a lancet (Accu-CheckSoftclix, UK), and the first drop of blood was wiped away. Pressure was applied to the earlobe with the thumb and forefinger in order to provide an adequate sample. A 5-μl sample of whole blood was automatically aspirated into a single use, enzyme-coated electrode test strip and analysed using and a hand-held portable analyser (Lactate Pro, Akray, Japan).

Statistical analysis

Statistical analysis was completed using IBM SPSS statistical software (v26.0 for windows, IBM corporation, Armonk, NY, USA). Normality of data was assessed using the Shapiro–Wilks test, with $p > 0.05$ used as the threshold for determination of normal distribution. Assumptions of homogeneity of variance were assessed using Levene's test with an alpha level of $p < 0.05$ determining a violation of the assumption. Independent sample t-tests were used to compare height and age between intervention groups (SIT vs. ET). A 2 × 2 mixed model ANOVA was used to compare the changes across time points and between groups. Time (pre and post training) was treated as the within group effect and training condition (SIT and ET) as the between-group effect for all outcome variables. Post-hoc analysis was conducted using a Bonferroni correction factor. Effect sizes were reported as partial eta squared (n^2) and values interpreted as 0.02 for small, 0.13 for medium and 0.26 for large. All values are reported as mean ± standard deviation.

Results

Over the 6 weeks of training, compliance was 100% in both the SIT and ET groups. Prior to starting the training intervention, there were no significant differences between SIT and ET groups for any physiological or performance

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Table 1 Anthropometric characteristics pre-training and in response to 6 weeks of training

	SIT		ET	
	Pre-training	Post-training	Pre-training	Post-training
Age (yrs)	26.5 ± 4.87		25.4 ± 2.58	
Height (cm)	178.5 ± 0.08		178.8 ± 0.05	
Mass (kg)	79.7 ± 9.64	79.7 ± 9.78	76.6 ± 9.72	76.6 ± 10.38
BMI (kg m^2)	25.3 ± 1.55	25.3 ± 1.51	23.5 ± 2.75	23.5 ± 2.90
Sum of skinfolds	120.6 ± 36.53	115.1 ± 36.90	98.0 ± 31.83	94.5 ± 33.10
Body fat (%)	16.9 ± 4.90	16.1 ± 5.04	13.5 ± 4.29	12.9 ± 4.60

Values are mean ± SD

BMI body mass index

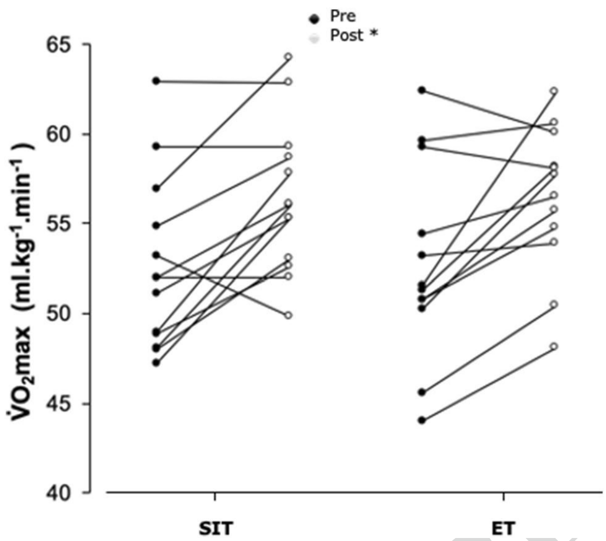

Fig. 2 Changes in maximal oxygen uptake ($\dot{V}O_2$max) in response to 6 weeks of sprint interval training (SIT) or endurance training (ET). Data are mean ± SD. Filled markers (□) represent pre-training values, and open boxes (□) represent post-training values. *Main effect for time ($p = 0.048$) vs. pre-training

variable. Participant characteristics are summarized in Table 1. There was no significant difference in age ($p = 0.52$) or height ($p = 0.94$) between SIT and ET and no significant main effects observed for body mass, BMI, sum of skinfolds and %body fat. Additionally, all variables were assessed for a group × time interaction, with three significant interactions observed (velocity at LT, VJ and 20 m running time).

Physiological parameters and intermittent endurance performance

There was a significant time effect for $\dot{V}O_2$max ($p = 0.048$, $F(1, 221) = 4.43$, $n^2 = 0.514$) in response to 18 sessions of SIT and ET (Fig. 2). There was also a significant time effect for HR_{max} ($p = 0.001$, $F(1, 21) = 15.69$, $n^2 = 0.428$), VE_{max} ($p = 0.048$, $F(1, 21) = 4.43$, $n^2 = 0.174$) and v$\dot{V}O_2$max ($p = 0.001$, $F(1, 21) = 14.68$, $n^2 = 0.411$) following both interventions (Table 2). The main effect of time for number of intervals completed during the intermittent endurance performance test was significantly different ($p < 0.001$, $F(1, 23) = 32.3$, $n^2 = 0.584$).

Table 2 Physiological and endurance performance parameters pre-training and in response to 6 weeks of training

	SIT		ET	
	Pre-training	Post-training	Pre-training	Post-training
VE_{max} (L min^{-1})	108.5 ± 10.26	115.9 ± 18.89*	107.7 ± 9.34	114.7 ± 12.74*
HR_{max} (bpm)	197 ± 7.71	192 ± 7.58*	197 ± 6.73	193 ± 5.57*
v$\dot{V}O_2$max (km h^{-1})	14.2 ± 1.28	15.2 ± 1.72*	13.7 ± 0.97	15.3 ± 2.31*
RPE_{max}	18.1 ± 1.85	19.1 ± 0.95	18.9 ± 1.31	19.0 ± 1.30
Vel. @ LT (km h^{-1})	10.4 ± 0.90	10.2 ± 1.07	9.8 ± 1.30	10.6 ± 1.08*
%$\dot{V}O_2$ at LT	73.8 ± 10.70	69.7 ± 9.64	69.5 ± 20.73	69.1 ± 6.74
%HR at LT	89.3 ± 3.38	84.5 ± 5.22	82.7 ± 10.02	83.8 ± 8.70
IEP (no. of intervals)	9.38 ± 4.21	12.9 ± 4.03*	8.00 ± 2.56	13.7 ± 4.60*

Values are mean ± SD

VEmax ventilation at maximal effort, *HRmax* heart rate at maximal effort, *RPEmax* rate of perceived exertion, *bpm* beats per min, *LT* lactate threshold, *IEP* intermittent endurance performance

*Main effect for time ($p < 0.05$) vs. pre-training

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There was a statistically significant interaction between exercise intervention and time, for velocity at LT, ($p = 0.012$), $F(1, 23) = 7.388$, $n^2 = 0.243$) with a statistically significant effect of time ($p = 0.025$, $t(11) = -2.59$, $n^2 = 0.379$) for velocity at LT for ET only (Table 2). There was no significant change in RPE_{max}, %HR and $\%\dot{V}O_2$ at LT (Table 2) or RE at 8, 9, 10 and 11 km h^{-1} (data not shown).

Running speed and lower body power

The main effect of time for Wingate mean power ($p = 0.001$, $F(1, 23) = 14.691$, $n^2 = 0.390$) and relative mean power ($p = 0.001$, $F(1, 23) = 14.167$, $n^2 = 0.381$) between pre and post intervention was significantly different (Table 3). In addition, the main effect of time for Wingate peak power ($p = 0.001$, $F(1, 23) = 13.831$, $n^2 = 0.376$) and relative peak power ($p = 0.001$, $F(1, 23) = 14.314$, $n^2 = 0.384$) between pre and post intervention was also significantly different. Finally, there was a significant time effect for fatigue index ($p = 0.050$, $F(1, 23) = 4.296$, $n^2 = 0.157$) in response to training in both ET and SIT groups.

Running speed over 5 m (SIT: pre, 1.13 ± 0.08 s, post, 1.13 ± 0.06 s; ET, pre, 1.13 ± 0.05 s, post, 1.15 ± 0.07 s) and CMJ performance (SIT: pre, 35.9 ± 5.82 cm, post, 35.0 ± 3.51 cm; ET, pre, 33.7 ± 5.13 cm, post, 33.1 ± 4.9 cm) were unchanged following the 6-week training intervention. There was however, a statistically significant interaction between the intervention and time for VJ ($p = 0.036$, $F(1, 22) = 5.007$, $n^2 = 0.185$) and 20 m running time ($p = 0.024$, $F(1, 22) = 5.880$, $n^2 = 0.211$). Further analysis identified no significant differences between groups pre and post training, but there was a statistically significant effect of time for VJ ($p = 0.003$, $t(11) = 3.735$, $n^2 = 0.559$) and for 20 m running time ($p = 0.006$, $t(11) = -3.52$, $n^2 = 0.553$), for the ET group only (Fig. 3).

Table 3 Wingate anaerobic performance test parameters pre-training and in response to 6 weeks of training

	SIT		ET	
	Pre-training	Post-training	Pre-training	Post-training
Mean power (W)	772.5 ± 99.2	828.1 ± 122.14*	725.9 ± 78.97	787.3 ± 133.21*
Mean power (W kg^{-1})	9.7 ± 1.12	10.4 ± 1.02*	9.5 ± 0.91	10.3 ± 0.68*
Peak power (W)	884.9 ± 134.9	927.5 ± 162.2*	813.1 ± 97.2	905.9 ± 155.1*
Peak power (W kg^{-1})	11.1 ± 1.44	11.6 ± 1.35*	10.7 ± 1.09	11.8 ± 0.97*
Fatigue index (%)	31.7 ± 4.19	28.7 ± 5.43*	31.7 ± 5.19	29.7 ± 3.92*

Values are mean ± SD

*Main effect for time ($p < 0.05$) vs. pre-training

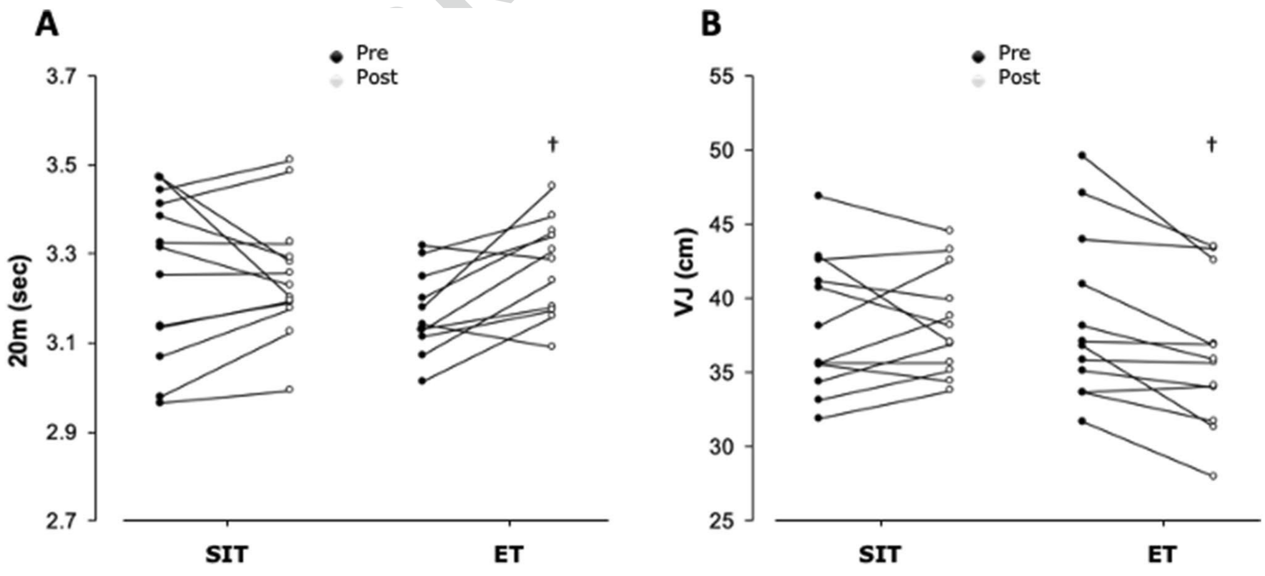

Fig. 3 Changes in **a** running time over 20 m and **b** jump performance during VJ, in response to 6 weeks of sprint interval training (SIT) and endurance training (ET). Data are mean ± SD. Filled markers (□) represent pre-training values, and open markers (□) represent post-training values. †Main effect for time ($p < 0.05$) vs pre training in ET group

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Discussion

In spite of a 55% difference in weekly training time, we observed beneficial, but different, performance-related adaptations to SIT and ET. The present study found that 6 weeks of SIT increased maximal oxygen uptake, IEP and Wingate performance to a similar extent as traditional ET. In contrast to ET, SIT maintained indices of running speed and jump performance in club level Gaelic football players. To our knowledge, the present study is the first to directly compare the effects of SIT and ET on indices of running speed and lower body power in trained field-based invasion team sport athletes.

Aerobic capacity and endurance performance

The increase in $\dot{V}O_2$max was similar after 6 weeks of SIT and ET despite large differences in training volume between groups. It is interesting that the relative increase in $\dot{V}O_2$max after 6 weeks in the present study (~7% in both groups) was similar to that observed in our previous work (Kelly et al. 2018), despite the considerably longer training period (2 vs. 6 weeks). This is supported by previous studies which have also found similar increases in $\dot{V}O_2$max following 2 weeks (Burgomaster et al. 2006; Bailey et al. 2009; Hazell et al. 2010; Astorino et al. 2011) and 6–8 weeks of SIT (Macpherson et al. 2011; Rowan et al. 2012; Cocks et al. 2013). The major physiological and biochemical adaptations to SIT may occur at an early stage of a training period and then plateau. Future work should investigate if SIT may be utilised initially in developing aerobic capacity, especially when time is a limiting factor, and whether less frequent conditioning may be then utilised as a maintenance tool. Burgomaster et al. (2007) used changes in the protein content of COX4 as a marker of changes in muscle oxidative capacity, and reported increases of approximately 35% after only 1 week of SIT, without further increase after 6 weeks of training (Burgomaster et al. 2007). A similar trend involving early stage adaptation followed by a plateau phase has also been reported in ET studies (Gaesser et al. 1984; Spina et al. 1996). Participants in these studies had a greater training volume (120 min per session) and/or frequency (12 sessions) when compared to the participants in the present study. A major advantage of SIT over ET is the reduced total time requirement. Our novel SIT program utilised both longer intra and shorter inter-set recovery periods in order to maintain the focus on targeting high-end capacities (all out efforts) during the session, while also contributing to the overall time efficiency of this training tool. The total time requirement in the current study was 840 min in the ET group and 374 min in the SIT group. Although not contributing to further improvements in aerobic capacity (~7% in both groups), SIT total exercise time (88 min) was 90% lower than ET (840 min), freeing up considerable collective training time that could be used to develop technical and tactical aspects of play.

The intermittent endurance performance test (IEP) involved a 20-min submaximal run (75% v$\dot{V}O_2$max) followed by alternating 1 min bouts of treadmill running between 75 and 100% v$\dot{V}O_2$max and was designed to be more specific to the intermittent nature and demands of field-based invasion team sports than a test involving continuous running to exhaustion. Maximal aerobic capacity and endurance exercise performance although related, are two distinct fitness attributes. The mean increase in $\dot{V}O_2$max of 6.7% after SIT and 6.8% after ET was supported by a significant increase in the number of IEP intervals the SIT (approx. 4 intervals) and ET group (approx. 6 intervals) were able to complete post training, with no difference between groups. In an applied setting, access to laboratory equipment and specialist testing expertise is not just costly but also time-consuming and may erode into the limited coach–player contact time. Previous work in youth and adult soccer players have found similar results (Sperlich et al. 2011; Nazarali et al. 2013), suggesting that simple field-based endurance performance tests may be used instead of expensive laboratory-based metabolic testing to detect improvements in endurance performance.

A significant increase in v$\dot{V}O_2$max following 6 weeks of SIT and ET coincided with increases in $\dot{V}O_2$max in both groups. v$\dot{V}O_2$max is a composite variable that combines $\dot{V}O_2$max and RE into a single factor and has been shown to be an important determinant of endurance exercise performance (Jones and Carter 2000). As there was no corresponding change in RE expressed as ml kg^{-1} min^{-1}, ml kg^{-1} km^{-1}, or kcal kg^{-1} km^{-1} at 8, 9, 10, or 11 km h^{-1} following SIT or ET, it is likely that the improvement v$\dot{V}O_2$max was elicited predominantly by an increase in maximal aerobic capacity. Studies have found improvements in RE following SIT in highly trained athletes and following both ET and SIT in trained soccer players (Helgerud et al. 2007; Iaia et al. 2009). The equivocal evidence on RE may be related in part to genetic differences or the fact that participants in previous studies had higher baseline aerobic capacity.

The increase in treadmill velocity at LT after 6 weeks of ET is consistent with previous ET studies (Hickson et al. 1981; Henritze et al. 1985; Helgerud et al. 2007). Endurance training at an exercise intensity close to the LT has been found to be an adequate training stimulus to increase the LT (Laursen and Jenkins 2002). A possible mechanism is an increased capillary density following endurance training leading to an increased exchange area and shorter distance between the site of lactate production and the capillary wall,

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resulting in an improvement in lactate exchange ability (Holloszy and Coyle 1984). SIT has also been found to be an effective strategy to alter lactate metabolism (Burgomaster et al. 2006) and it has been suggested that trained athletes need to exercise at a higher relative exercise intensity to increase LT (Londeree 1997). Higher intensity training has been reported to maintain concentrations of monocarboxylate transporter (MCT) proteins, used to regulate lactate and H^+ exchange in human skeletal muscle, while concentrations fell for those training at lower intensities (Evertsen et al. 2001). The fact that the treadmill velocity, relative HR, $\dot{V}O_2$ at LT and fixed blood lactate concentrations did not improve following 6 weeks of SIT was surprising. Our previous work (Kelly et al. 2018) investigating 2 weeks of SIT and ET on blood lactate markers suggested that the stimulus experienced during training and the duration of the training period were possibly the limiting factors in lowering blood lactate levels at the same absolute workloads following SIT and ET. Our present study findings indicate that a minimum duration of exercise (> 2 weeks) is possibly required to induce significant decreases in blood lactate markers following ET. Although the exercise stimulus during our SIT protocol's and subsequent duration of elevation in blood lactate may be too brief or possibly not effective at improving blood lactate markers, it is possible that SIT may induce a tolerance to blood lactate accumulation in field-based team sport players.

Although previous work investigating the benefits of SIT on aerobic capacity and endurance performance is well established (MacInnis and Gibala 2017), the increase in these parameters in the present study was found using a simple, bidirectional running protocol without the need for any specialised equipment. In addition, these improvements were observed in trained field-based invasion team sport athletes and by utilising this protocol design, participants trained specifically to the demands of their sport. As the training effect that occurs in response to an exercise overload is specific to the way in which the load is applied (principle of specificity), SIT protocols (running vs cycling) should be designed with the specific movement patterns of the training athlete in mind.

Running speed and lower body power

Average improvements of 6–8% in mean power (MP) and peak power (PP) during 30-s Wingate cycling tests in active college age students following SIT have been well documented (MacDougall et al. 1998; Burgomaster et al. 2006; Hazell et al. 2010). The magnitudes of increase in Wingate PP (5%) and MP (7%) in the present study are comparable with these previous investigations. Furthermore, fatigue index improved significantly in the SIT (9.4%) and ET (6.2%) groups following the 6-week intervention highlighting the fact that both training methods contribute to fatigue resistance during repeated intense anaerobic efforts. This type of training adaptation is highly likely to impact performance in an intermittent high-intensity sport such as Gaelic football, which is characterized by irregular changes of pace and repeated short-duration bouts of high-intensity activity. However, it is possible that the Wingate test lacks the specificity required to assess lower body power in field-based invasion team sport athletes, given that it is a cycle ergometer-based test. Therefore, more specific assessment of lower body power (e.g. jump performance testing), as regularly used in the profiling of field-based invasion team sport athletes (Cullen et al. 2012; Daly et al. 2020), is warranted.

A novel aspect of the present study was the use of practical measurements of running speed (5 and 20 m) and jump performance (VJ and CMJ) of field-based invasion team sport athletes. Previous work that has investigated running speed following SIT in team sport athletes has utilised tests (MacPherson et al. 2011) more closely related to anaerobic capacity than running speed and as mentioned, tests of power output previously utilised have lacked specificity (Wingate). Although the primary aim of SIT is to elicit adaptations in aerobic endurance performance, it is possible that it may also induce neuromuscular and endocrine adaptions that have a positive effect on running speed and power, both key fitness characteristics for optimal performance in field-based invasion team sport. Surprisingly, there was no significant change in running speed (− 0.1%), CMJ (− 0.3%) or VJ (− 0.7%) indices following SIT. However, time to complete a 20-m sprint increased significantly (3.2%) and VJ performance decreased significantly (6.5%) following 6 weeks of ET. Considering that both running speed and power are essential components of fitness for players in many invasion field games, it is surprising that relatively few published studies have evaluated the effect of SIT and ET on these indices. Previous research among adolescent soccer players found that strength-related power output but not jump performance is impaired following a period of endurance training (Sperlich and Koehler 2011). It is possible however, that the addition of soccer-specific training in addition to the ET protocol may have contributed to the maintenance of jump performance (Nelson et al. 1990). To the authors' knowledge, this is the first study to simultaneously compare the effects of standalone SIT and ET on indices of running speed and lower body power in trained team sport athletes.

It is likely that the potency of SIT is derived in large part from the high level of motor unit activation. The high exercise intensities (i.e., ≥ 90% of maximal sprinting speed) and the changes of direction experienced during SIT lead naturally to high engagement of both neuromuscular and musculoskeletal systems. The maintenance of running speed, jump height and power in response to SIT may have been due, in part, to the fact that both fast twitch type IIa and type IIX muscle fibres were recruited

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to supply the high force demands during training. Muscle fibre recruitment is determined by force requirements, with the slow muscle fibres being activated for low force contractions and increasingly fast muscle fibres being additionally activated to supply greater force demands (size principle) (Henneman and Clamann 1974). While ideal for developing aerobic capacity, ET may lack the specificity required to develop and/or maintain running speed and muscle power, whereas SIT may induce positive functional performance adaptations (Hennessy and Watson 1994) that allow for a similar improvement in aerobic capacity but with the concurrent maintenance of anaerobic performance. It is likely that ET involved recruitment of primarily slow twitch and type IIa fast twitch motor units as training with a large aerobic energy involvement and little neuromuscular stress (ET) elicits low type 2 fibre recruitment due to low force demands. Since type IIa fast twitch fibres display considerable plasticity in relation to their biochemical and morphological properties when exposed to different functional demands (Schiaffino and Reggiani 2011), it is possible that ET induced remodelling resulting in some fibres taking on many of the morphological and biochemical characteristics of slow twitch fibres. Although beneficial for improving endurance exercise performance, these adaptations do not provide the desired loading for type IIx fibres to maintain indices of speed and power. Considering that ET is commonly used in the preparation of players for many field-based invasion team games, it is interesting that relatively few published studies have simultaneously evaluated the effect of this form of training (ET) on running speed and jump performance of invasion team sport players.

The magnitude and variability of individual response resulting from high-intensity interval training has been well documented (Gibala et al. 2006; Burgomaster et al. 2008; Purkhús et al. 2016) and was observed for a number of variables in the current study. The factors that determine this individual response are still unknown, but may include hereditary fitness level, age, gender, the duration of the training program and the intensity, duration and frequency of the individual training sessions. Genetic factors establish the limit for each individual, but training can push athletic performance to the upper limits of these boundaries. SIT induces physiological and biochemical adaptations linked with improvements in $\dot{V}O_2$max that have been typically associated with high-volume endurance training including muscle oxidative capacity, muscle buffering capacity and nuclear abundance of PGC-1α (Gibala et al. 2006; Burgomaster et al. 2008; Little et al. 2010). Further investigations should examine more closely the long-term effect and potency of SIT, the underlying factors influencing high and low responders and the cellular and molecular mechanisms underpinning the response of aerobic capacity, running speed and power to SIT and ET.

Conclusion

Coaches have limited time with players and, therefore, need to optimize contact time. The SIT protocol used in this study requires few resources and can be completed using only a stopwatch, 60–70 m of space, and without the need for supervision, expertise or specialist monitoring equipment. To optimise field-based invasion team sport performance, most athletes require not only high levels of cardiorespiratory fitness but also aspects of enhanced maximal strength, power and speed. SIT provides a more time-efficient training method than ET for improving aerobic capacity and maintaining indices of running speed and power in club-level Gaelic football players. If traditional ET is to be used as a conditioning tool, it may be worthwhile to include additional high-velocity or sport-specific training in order to generate a sufficient stimulus to maintain indices of speed and power. In order to optimise training time, avoid interference and enhance adaptation, other factors that need to be considered when designing or implementing SIT into a training program are the current conditioning level of the athletes, training history, individual player demands and the training periodization plan.

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Data availability The data that support the findings of this study is available upon reasonable request.

Declarations

Conflict of interest None of the authors have a conflict of interest to declare.

Ethical approval Dublin City University Ethical Committee approved the study and included procedures/analyses.

Consent to participate Participants gave their written informed consent to take part in the present investigation.

Consent for publication The present authors all consent to the publication of this work.

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