NRC Research Press

ARTICLE

Effects of high-intensity running training on soccer-specific fitness in professional male players

Carl Wells, Andrew Edwards, Mary Fysh, and Barry Drust

Abstract: The purpose of this study was to investigate whether or not physiological and performance gains could be achieved with the addition of high-intensity running to an existing training programme in a group of well trained professional male soccer players. Sixteen professional male players (21.3 ± 2.1 years, stature 177.4 ± 4.2 cm, body mass 73.1 ± 8.1 kg) were randomised in training (TRA, $n = 8$) and control (CON, $n = 8$) groups. All players performed physiological assessments before and after a 6-week intervention. Outcome measures were: (*i*) $\dot{V}O_{2peak}$, (*ii*) $\dot{V}O_2$ kinetics during very heavy-intensity exercise, (*iii*) a maximal anaerobic running test, and (*iv*) Yo-Yo Intermittent Recovery Test level 2 (YIRT2). The only aerobic parameter to change after the intervention was the phase III time constant at exercise onset for CON, which lengthened ($p = 0.012$) to a value similar to that of the TRA group. However, TRA showed gains in anaerobic performance ($p = 0.021$), time to exhaustion ($p = 0.019$), and maximal running speed ($p = 0.023$). In the YIRT2, distance run increased for TRA over time ($p = 0.015$), and the TRA group were also capable of running further in the YIRT2 after the intervention compared with CON ($p = 0.011$). This study shows it is possible to improve the soccer-specific high-intensity running capacity of professional players when high-intensity intermittent training is added to the normal training load and that this effect is only detectable in anaerobic capabilities. The observed effects are meaningful to the training practices of elite athletes seeking a competitive edge in team sports when otherwise well matched.

Key words: sport-specific, conditioning, anaerobic, oxygen dynamics.

Résumé : Cette étude se propose de vérifier si l'ajout de séances de course de haute intensité à un programme d'entraînement déjà établi suscite des gains physiologiques et de performance chez des joueurs de soccer professionnel bien entraînés. On répartit aléatoirement seize joueurs professionnels (21,3 ± 2,1 ans, 177,4 ± 4,2 cm, 73,1 ± 8,1 kg) dans deux groupes : entraînement (TRA, $n = 8$) et contrôle (CON, $n = 8$). On évalue les variables physiologiques avant et après 6 semaines d'intervention : (*i*) $\dot{V}O_{2\text{de pointe}}$, (*ii*) cinétique du $\dot{V}O_2$ au cours d'un exercice très intense, (*iii*) test maximal de course en anaérobiose et (*iv*) test yo-yo de niveau 2 avec récupération intermittente (YIRT2). La seule variable aérobie modifiée à la suite de l'intervention est la constante de temps de la phase III au début de l'exercice dans le groupe CON : elle augmente ($p = 0,012$) jusqu'à une valeur similaire à celle du groupe TRA. Toutefois, le groupe TRA présente les gains suivants : performance anaérobie ($p = 0,021$), temps jusqu'à l'épuisement ($p = 0,019$) et vitesse maximale de course ($p = 0,023$). Au YIRT2, la distance de course augmente avec le temps dans le groupe TRA ($p = 0,015$); en outre, comparativement au groupe CON, le groupe TRA court davantage dans le YIRT2 après l'intervention ($p = 0,011$). Cette étude démontre la possibilité d'améliorer la capacité de course de haute intensité spécifique au soccer professionnel quand on ajoute un programme d'entraînement intermittent de haute intensité, mais cette amélioration n'est détectable que dans les capacités anaérobies. Ces observations sont pertinentes pour les séances d'entraînement des athlètes d'élite désireux de se démarquer dans un sport d'équipe où les autres variables sont apparentées. [Traduit par la Rédaction]

Mots-clés : spécificité sportive, conditionnement physique, anaérobiose, dynamique de l'oxygène.

Introduction

Identification of the physiological determinants of performance during multiple-sprint sports such as soccer has yet to occur because of the diverse physical demands of competitive match play (Edwards and Noakes 2009; Mohr et al. 2003). Elite-standard soccer is, in part, dependent on cardiopulmonary fitness because of the distances a player is required to run. This was demonstrated by Helgerud et al. (2001), who reported that an increase in the maximal oxygen uptake ($\dot{V}O_{2max}$) of elite adolescent soccer players was associated with a 100% increase in the number of sprints they performed during matches. However, more recent research has demonstrated that $\dot{V}O_{2max}$ is not correlated to high-intensity exercise during a game (Mohr et al. 2003) and has not consistently been shown to reflect short-term changes in the training condition of elite soccer performers (Clark et al. 2008; Edwards et al. 2003; Wells et al. 2012). As a result, several researchers have proposed that a $\dot{V}O_{2max}$ of approximately 60 mL·kg^{-1}·min^{-1} is a minimal requirement for elite professional male soccer performance (Bangsbo 1994; Reilly et al. 2000), but that it is not necessarily a determinant of performance (Edwards and Noakes 2009).

Alternative indicators of soccer players' aerobic status such as oxygen uptake ($\dot{V}O_2$) kinetics have received little attention. Recently, Wells et al. (2012) reported that phase II $\dot{V}O_2$ kinetics, both to the onset and cessation of very heavy intensity running, did not discriminate between soccer players who differed in their abilities to perform high-intensity soccer-specific running. However, firm conclusions about the role of $\dot{V}O_2$ kinetics in soccer performance cannot be drawn from these findings as they were based on a

Received 13 May 2013. Accepted 16 December 2013.

C. Wells and M. Fysh. Sheffield Hallam University, Centre for Sport and Exercise Science, Sheffield, UK.
A. Edwards. James Cook University, Institute of Sport and Exercise Science, Cairns QLD 4879, Australia.
B. Drust. Liverpool John Moores University, School of Sport and Exercise Sciences, Liverpool, UK.
Corresponding author: Andrew Edwards (e-mail: andrew.edwards@jcu.edu.au).

cross-sectional comparison of elite and nonelite players, which did not permit assessment of the relationship between changes in $\dot{V}O_2$ kinetics and high-intensity running capacity.

As a considerable proportion of the runs classed as high speed during a game are above those that correspond to the anaerobic threshold and $\dot{V}O_{2max}$, it is conceivable that it is a player's ability to either respond rapidly to an exercise challenge ($\dot{V}O_2$ kinetics) or to exercise anaerobically that might be decisive factors for elite soccer performance. Although previous studies (Edwards et al. 2011; Krustrup et al. 2003; Mohr et al. 2003) have alluded to a high level of anaerobic fitness as being fundamental for the performance of soccer-specific high-speed running, none have yet stated how it would benefit performance. A large anaerobic capacity indicates that an individual has an enhanced ability to derive large amounts of energy from the ATP-PC and glycolytic systems (Bangsbo and Michalsik 1993). This would potentially enable prolonged performance of supra-$\dot{V}O_{2max}$ running speeds.

Evidence for this hypothesis is provided by Ramsbottom et al. (2001), who noted that after high-intensity training, improved time to exhaustion in a continuous shuttle run at 120% of $\dot{V}O_{2max}$ was matched by an increase in maximal accumulated oxygen deficit (MAOD) but not $\dot{V}O_{2max}$. Similarly, Roberts et al. (1982) reported increases in run time to exhaustion during a supra-$\dot{V}O_{2max}$ run (16 km·h^{-1} at 15% incline) after 5 weeks of high-intensity training was associated with increases in ATP derived from anaerobic glycolysis rather than aerobic metabolism. Further support is provided by the findings that 400 m runners who are required to run at supra-$\dot{V}O_{2max}$ speeds for approximately 45 s have a considerably larger anaerobic capacity as indicated by the maximal anaerobic running test (MART) than middle and long-distance runners (Edwards et al. 1999, 2011; Nummela et al. 1996). In contrast, MAOD values have been reported as similar for a range of elite athletes whose sports required distinctly different anaerobic contributions (Bangsbo and Michalsik 1993; Demarle et al. 2001). The same authors also reported a large variation in MAOD among a group of elite soccer players, leading them to conclude that performance in soccer is actually determined by the rate of aerobic energy turnover or, alternatively, anaerobic energy production might not be limiting to performance.

It has been reported that if a player performs 2 or more high-intensity training sessions per week in addition to their normal training regime, improvements occur to their high-intensity running capacity (Bangsbo 1994). This is meaningful for performance as a player with greater high-intensity running ability could sprint more effectively at a key stage of a match, making the difference between winning and losing (Edwards and Noakes 2009). As well-trained professional soccer players already undertake a variety of training modalities, the inclusion of a high-intensity programme to their usual practice would establish if this represents a meaningful addition to their training routine. It has previously been demonstrated (Krustrup et al. 2003, 2005) that 25% and 10% improvements are possible in response to the soccer-specific Yo-Yo Intermittent Recovery Running Test Level 2 (YIRT2) following 8 weeks of repeated 30 s and 10 s sprint training programmes, respectively. It has been suggested that the greatest performance gains are achieved if the training undertaken is sport specific (Bangsbo 1994; Wells et al. 2012). Hence, an intermittent exercise model should be used that incorporates a range of soccer-specific running speeds (Boobis 1987; MacDougall et al. 1998). Therefore, the aims of this study were: (*i*) to identify if the addition of 6 weeks of high-intensity running to a soccer training programme improves selected performance variables relevant to soccer performance and (*ii*) to identify if changes in aerobic ($\dot{V}O_{2max}$, gas exchange threshold, on- and off-transient $\dot{V}O_2$ kinetics) or anaerobic (anaerobic capacity) physiological measures accompany changes in sports-specific variables across the 6-week period.

Table 1. The 6-week high-intensity intermittent training schedule followed by the training group.

	Session sets and repetitions		
Week	1	2	3
1	4×60s(2+2)	6×35s(3+3)	10×10s(5+5)
2	4×60s(2+2)	6×35s(3+3)	10×10s(5+5)
3	6×60s(3+3)	8×35s(4+4)	12×10s(6+6)
4	6×60s(3+3)	8×35s(4+4)	12×10s(6+6)
5	8×60s(4+4)	10×35s(5+5)	14×10s(7+7)
6	8×60s(4+4)	10×35s(5+5)	14×10s(7+7)

Materials and methods

Participants

With institutional ethics approval, 16 male professional soccer players ((mean ± SD): age 21.3 ± 2.1 years, stature 177.4 ± 4.2 cm, body mass 73.1 ± 8.1 kg) were recruited for this study and provided informed consent. The aim of the study was clearly explained and the possible risks were outlined. All the players had been full-time professionals for at least 2 years and were recruited from the same club. Players were randomly allocated to either the training (TRA, n = 8) or control (CON, n = 8) group. Prior to the administration of any test, participants completed a medical screening questionnaire to identify any conditions that might become aggravated during the testing procedure. No conditions were identified by the participants.

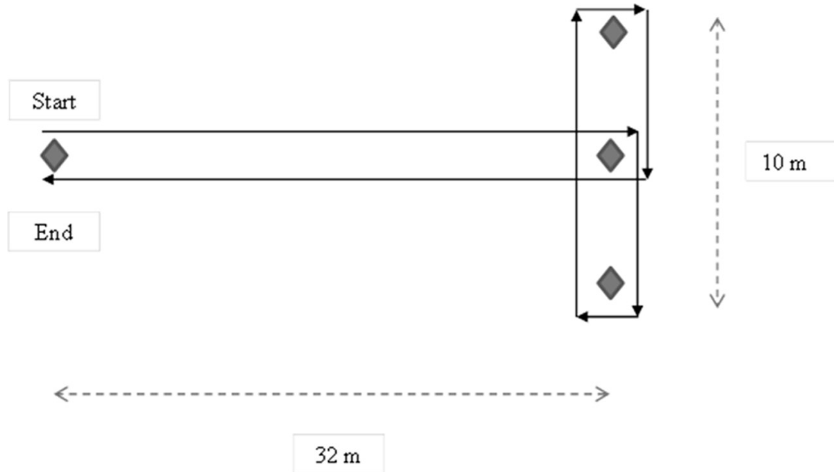
Experimental design

All participants performed 4 physiological assessments in the following order, each separated by 4 days, a standardised process repeated post-intervention. The assessments were (*i*) a laboratory-based incremental exercise test to exhaustion to assess $\dot{V}O_{2max}$, (*ii*) repeated very heavy intensity square-wave protocol for the assessment of high-intensity on- and off-transient $\dot{V}O_2$ kinetics (Özyener et al. 2001), (*iii*) the MART for an indication of anaerobic capacity, and (*iv*) the sport-specific YIRT2. Following completion of the 4 assessments the TRA group undertook a 6-week high-intensity running programme (Table 1) in addition to the club's normal training regime performed by the CON group (comprising 4.7 ± 1.1 training sessions of 1.5 hr and 1.2 ± 0.4 matches of 90 min per week). There was no difference between compliance and adherence to the training regime between groups. All players performed standardised in-season training that comprised technical, skill, and fitness activities in addition to small-sided games. Therefore, the high-intensity running programme was simply an additive training factor to ascertain whether this facilitated additional performance gains to the cohort's (TRA and CON) normal training practice. After the sixth week, the assessments were repeated for both TRA and CON groups to identify if the intervention had influenced any of the physiological and performance measures. On each visit to the laboratory the participants' stature and body mass were measured and heart rate (HR) was recorded at 5 s intervals during each assessment. All assessments were performed at the same time of day to reduce the effects of diurnal variation and the temperature of the laboratory was standardised to 20 °C ± 1 °C.

Experimental protocols

All laboratory-based exercise tests were performed on a motorised treadmill (Saturn, HP Cosmos, Nussdorf – Traunstein, Germany). Pulmonary gas exchange was analysed breath-by-breath (CPX/D, Medgraphics Corporation, St Paul, MN, USA) during the incremental exercise test to exhaustion for the identification of variables derived from expired air and also running speeds that corresponded to (*i*) $\dot{V}O_{2max}$, (*ii*) gas exchange threshold (GET), and (*iii*) 80%Δ $\dot{V}O_2$. These running speeds were then used to design a repeated very heavy intensity square-wave transition protocol that consisted of 4 6-min runs at 80%Δ. Each run was separated by

Fig. 1. A running course performed at approximatley 30 km·h^{-1} for repeated 10 s bouts during the training intervention (→ running direction, ------ course dimensions).



a 12 min walk and a further 30 min of passive recovery in accordance with earlier experiments (Wells et al. 2012). Pulmonary gas exchange was measured throughout the test (CPX/D, Medgraphics Corporation, St Paul, MN, USA) to determine $\dot{V}O_2$ kinetics during the onset and cessation of very heavy intensity treadmill running.

The final laboratory test was the MART (Nummela et al. 1996). Briefly, the test used the standard MART procedure involving 20 s running bouts separated by 100 s of passive recovery. The starting speed was 14.3 km·h^{-1} and increased by 1.2 km·h^{-1} for each subsequent 20 s run. The gradient of the treadmill belt was kept at 10.5%. The participants completed as many 20 s runs as possible until exhaustion. Performance in the MART provided a measure termed by the researchers as anaerobic power that because of its strong association (r = 0.81) with MAOD (MacDougall et al. 1998) is used as an indicator of anaerobic capacity.

The field-based sport-specific YIRT2 test was performed outdoors on a dry artificial grass surface at temperatures similar to those of the laboratory (range: 16–20 °C). The YIRT2 is an incremental and maximal test that provides a measure of high-intensity intermittent running capacity. The test involved running back and forth along a 25 m track in an intermittent fashion. The running speed was dictated by audio signals generated from a standardised, prerecorded audio track. Once participants were unable to maintain the required running speed as dictated by the audio recording on 2 continuous occasions they were withdrawn from the test. The test outcome is the total distance covered and protocol for the YIRT2 is in accordance with previous studies (Mohr et al. 2003; Wells et al. 2012).

High-intensity training programme

The training programme ran for 6 weeks and consisted of 3 running sessions per week, all performed outside on a soccer pitch with a natural grass surface. The running involved performing predetermined courses of different lengths that incorporated changes in direction to replicate the demands of soccer. The volume of the training was gradually increased over the 6 weeks and its structure is listed in Table 1. Sets of repetitions were split into sub sets, with 2 min of active recovery separating each sub set. Based on match analysis data (Van Gool et al. 1988; Mohr et al. 2003) each running course was performed at speeds that spanned the high-intensity spectrum (≥18 km·h^{-1} to maximum sprint speed) of soccer performance as follows: session 1, approximately 19 km·h^{-1}; session 2, approximately 24 km·h^{-1}; and session 3, maximal sprint, approximately 30 km·h^{-1}. The duration of the runs were set at 60 s, 35 s, and 10 s for sessions 1, 2, and 3, respectively, to ensure that the players were capable of maintaining the desired speed for each run of each session. Players were instructed to complete each running course within a predetermined time to ensure they were running at the correct speed. The exercise to recovery ratio was 1:3, as this has previously been used in a training study that reported an increase in high-intensity shuttle running capacity (Ramsbottom et al. 2001). The recovery periods consisted of low-intensity jogs back and forth along a 10 m track. Heart rate (HR) was recorded for each session as it was intended that the participants would be exercising at ≥95% of HRmax. Before and after each running session participants performed an appropriate 10 min warm-up and cool down. A representation of one of the running circuits is shown in Fig. 1.

Data analysis

Breath-by-breath pulmonary gas exchange data collected during the incremental exercise tests and repeated square-wave transition protocol were analysed following the procedures outlined in previous publications (e.g., Wells et al. 2012).

Statistical analyses

Groups were compared by a mixed design factorial 2-way analysis of variance (ANOVA). Pearson's correlation was conducted to assess the strength of association between measures before and after the training intervention. Significance was set at p < 0.05.

Results

Incremental exercise test performance

A 2-way ANOVA mixed design found measures of aerobic fitness and exercise performance recorded taken from the incremental exercise test to exhaustion did not differ (p > 0.05) between or within the TRA and CON groups before or after the training intervention (Table 2).

Measures of $\dot{V}O_2$ kinetics

The mean $\dot{V}O_2$ kinetic on-transient parameters for the TRA and CON groups before and after the training intervention analysed by mixed design 2-way ANOVA revealed no difference for τ_1 between (τ_{1on}, p = 0.475; τ_{1off}, p = 0.832) or within (τ_{1on}, p = 0.568; τ_{1off}, p = 0.736) TRA and CON before or after the training intervention for either on- or off-transient of exercise (Table 3). Before the intervention CON had a quicker τ_{2on} (p = 0.039) than that of the TRA (CON τ_{2on}, 96.4 ± 38.7 s vs. TRA τ_{2on}, 133.8 ± 77.5 s). After the intervention however, τ_{2on} for the CON increased (p = 0.012) to a value similar to that of the TRA group (CON τ_2, 139.5 ± 55.7 s vs. TRA τ_2, 131.3 ± 107.1 s). As a consequence, the phase III oxygen deficit (DO_2) was found to differ before and after the intervention

Table 2. Values (mean ± SD) for aerobic and performance measures recorded from the incremental exercise test before and after the training intervention for the TRA (n = 8) and CON (n = 8) groups.

	CON (n = 8)		TRA (n = 8)	
Measure	Before	After	Before	After
$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	57.1±3.6	57.6±3.1	57.6±5.4	58.9±4.7
GET (ml·kg^{-1}·min^{-1})	41.8±1.7	40.3±1.7	42.5±3.6	42.8±4.4
GET % of $\dot{V}O_{2max}$	71±4.3	72±3.4	70±4.2	69±3.2
HR max (beats·min^{-1})	192±8	193±7	191±6	193±6
Max speed (km·h^{-1})	19.0±0.9	18.6±0.6	19.2±1.2	19.1±0.9
Time to exhaustion (s)	708±54	702±30	705±73	709±74

Note: CON, control group; TRA, training group; GET, gas exchange threshold.

Table 3. The physiological and $\dot{V}O_2$ kinetic parameters (mean ± SD) measured during the on-transient of very heavy-intensity treadmill running for the CON (n = 8) and TRA (n = 8) groups before and after the training intervention.

	CON (n = 8)		TRA (n = 8)	
Measure	Before	After	Before	After
HR (beats·min^{-1})	174±7	176±5	178±9	176±4
T_{D1} (s)	7.8±3.5	8.6±2.2	8.9±3.8	8.2±3.1
T_{D2} (s)	125.4±11.7	128.3±9.4	124.2±13.2	126.6±12.8
τ_1 (s)	25.7±1.9	24.3±2.9	24.6±4.2	24.1±2.3
τ_2 (s)	96.4±38.7*	139.5±55.7	133.8±77.5	131.3±107.1
A_1 (mL·min^{-1})	2859±114	2774±142	2802±226	2673±185
A_2 (mL·min^{-1})	363±23	379±54	323±71	355±155
DO_2 for phase II (mL)	1478±39	1437±47	1458±52	1423±36
DO_2 for phase III (mL)	916±55*,**	1045±61	1009±78	1028±57
DO_2 total (mL)	2394±62	2482±47	2467±89	2451±75

Note: *Difference before and after the intervention for corresponding values within the same group $p < 0.05$. **Difference before the intervention for corresponding values between the different groups $p < 0.05$. (CON, control group; TRA, training group; TD, xxxxx; A, xxxxx; DO_2, oxygen delivery.)

within the CON group (p = 0.041) and between the CON and TRA groups (p = 0.038). This is further supported by a significant interaction between player group and time of measurement for phase III DO_2 (p = 0.036). However, this difference in phase III DO_2 was not large enough to cause a difference in the total DO_2 (phase II DO_2 + phase III DO_2) for the onset of exercise, with no difference observed within (p = 0.176) or between (p = 0.218) groups before or after the intervention for total DO_2. There was also no interaction between time of measurement and player group for total DO_2 (p = 0.071). Phase II DO_2 values between (p = 0.195) and within (p = 0.276) groups were very similar before and after the intervention. There was no interaction between player group and time of measurement for Phase II DO_2 (p = 0.572). No difference was found for τ_{2off} before or after the intervention within (p = 0.319) or between (p = 0.461) groups (Table 4). There was also no interaction between time of τ_{2off} measurement and player group (p = 0.368). An example response is shown in Fig. 2.

MART performance

Measures obtained from the MART are listed in Table 5. The 2-way ANOVA mixed design revealed the anaerobic power (p = 0.021), time to exhaustion (p = 0.019), and maximal running speed (p = 0.023) to only increase for the TRA group following the training intervention and, as a result, were greater for the TRA than the CON group (anaerobic power, p = 0.024; time to exhaustion, p = 0.012; maximal running speed, p = 0.037). Blood lactate did not differ between (p = 1.217) or within groups (p = 1.246) before and after the training intervention.

YIRT2 performance

A 2-way mixed ANOVA showed that following the training intervention, distance run increased for the TRA over time (p = 0.015), consequently the TRA group were capable of running further in the YIRT2 after the intervention compared with the CON group (p = 0.011).

Relationship between YIRT2 performance and physiological measures

The association detected between YIRT2 performance and $\dot{V}O_{2max}$ was not found to change before or after the training intervention for the CON (pre: r = 0.71, p = 0.041; post: r = 0.73, p = 0.033) or TRA groups (pre: r = 0.69, p = 0.031; post r = 0.70, p = 0.030). In comparison, τ_{1on} was inversely related with YIRT2 performance before and after the intervention for the TRA (pre r = −0.65, p = 0.032; post: r = −0.66, p = 0.034) and CON (pre: r = −0.75, p = 0.029; post: r = −0.71, n = 8, p = 0.030) groups, although no change in the strength of the association between measures was apparent for either group. The τ_{1off} was not related to YIRT2 performance before or after the intervention for either TRA (pre: r = −032, n = 8, p = 0.068; post: r = −0.28, n = 8, p = 0.067) or CON (pre: r = −0.39, n = 8, p = 0.061; post r = −0.34, n = 8, p = 0.066) groups.

After the training intervention, stronger relationships existed between YIRT2 performance and the MART measures of power (pre: r = 0.81, p = 0.023; post: r = 0.89, p = 0.014), maximal speed (pre: r = 0.74, p = 0032; post: r = 0.84, p = 0.016), and time to exhaustion (pre: r = 0.81, p = 0.021; post: r = 0.85, p = 0.015) for the TRA group. However, there was no noticeable change in these associations after the intervention for the CON group: power (pre: r = 0.78, p = 0.028; post: r = 0.75, p = 0.029), speed (pre: r = 0.72, p = 0.033; post: r = 0.72, p = 0.033), and time to exhaustion (pre: r = 0.76, p = 0.029; post: r = 0.77, p = 0.024). Relationships between the changes in variables were only found to exist for the TRA group. Associations were observed (Fig. 3A to 3C) between the increases in YIRT2 performance and MART power (r = 0.89, p = 0.013), time to exhaustion (r = 0.90, p = 0.011), and maximal speed (r = 0.87, p = 0.015), with no association being revealed between YIRT2 performance improvement and any other physiological measure.

Discussion

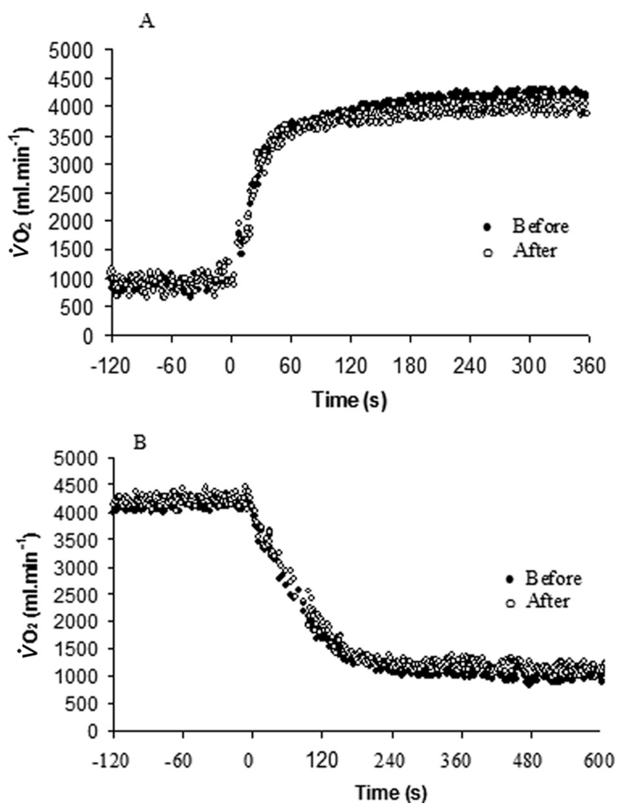
The main observation of this study shows that it is possible to improve the soccer-specific high-intensity running capacity of

Table 4. The $\dot{V}O_2$ kinetic parameters (mean ± SD) measured during the off-transient of very heavy-intensity treadmill running for the CON (n = 8) and TRA (n = 8) groups before and after the training intervention.

	CON (n = 8)		TRA (n = 8)	
Measure	Before	After	Before	After
T_{D1} (s)	8.9±3.2	9.4±3.4	8.4±4.1	8.7±3.7
τ_1 (s)	29.1±1.6	28.3±1.8	30.3±1.2	29.8±1.1
τ_2 (s)	314.6±56.2	295.3±42.5	300.4±65.6	275.4±43.6
A_1 (mL·min^{-1})	2604±122	2634±171	2797±100	2892±105
A_2 (mL·min^{-1})	131±32	124±41	118±48	129±39

Note: A 2-way mixed design ANOVA indicated that A_1 did not differ between (A_{1on}, p = 0.746; A_{1off}, p = 0.474) or within (A_{1on}, p = 0.274; A_{1off}, p = 0.216) groups before or after the training intervention for either exercise transient. These findings were replicated for A_{2on} and A_{2off} between (A_{2on}, p = 0.328; A_{2off}, p = 0.104) and within (A_{2on}, p = 0.735; A_{2off}, p = 0.093) groups. There was no interaction for A_{2off} between time of measurement and player group (p = 0.142). (CON, control group; TRA, training group; TD, xxxxx; A, xxxxx.)

Fig. 2. The $\dot{V}O_2$ response to the on-(A) and off-transients (B) of very heavy-intensity treadmill running for a representative participant (2) from the Training group (n = 8) before (●) and after (○) the training intervention.



professional soccer players when 6 weeks of high-intensity intermittent training is added to their normal training regime. This was a low intrusion addition to existing training practices among a group of professional players performing well-established training practices (Reilly et al. 2000). As high-speed running capacity has been shown to distinguish between international and domestic standard players (Mohr et al. 2008), the addition of a high-intensity running programme to existing training practices might be meaningful to enhancing a professional soccer player's capabilities. This may be useful in periods such as preseason training and particularly for individual players identified in need of further development (Reilly et al. 2000; Edwards and Noakes 2009). It should be noted that the increase in training load due to additional training practises must be appropriately managed to minimise injury occurrence.

The TRA group improvement in YIRT2 performance of 13.1% was matched by an 8.7% increase in anaerobic power derived from the MART. Mechanistically this suggests that post-intervention anaerobically derived performance gains are possible within 6 weeks among professional players with no associated change in aerobic measures such as $\dot{V}O_{2max}$ or $\dot{V}O_2$ kinetics or reports of discomfort or injury consequent to the inclusion of this additional programme. The 2 groups were well matched for aerobic capabilities and the observed effects may be meaningful to the training practices of elite athletes seeking a competitive edge in team sports when otherwise well matched for aerobic capabilities such as in the TRA and CON groups of this study.

The change in YIRT2 for the TRA group is in accordance with improvements reported for elite soccer players (Krustrup et al. 2003) performing level one of the test. The improvement in MART performance is greater than that of 3.4% previously observed for elite sprinters following 10 weeks of training (Nummela et al. 1996), and it was sufficient to give the players an anaerobic power (124.2 ± 5.2 mL·kg·min^{-1}) comparable to that previously reported (Nevill et al. 1989) for elite 400 m runners (122.6 ± 4.9 mL·kg·min^{-1}).

Significant relationships were observed before and after the training intervention between YIRT2 performance and $\dot{V}O_{2max}$, GET, τ_{1on}, and the anaerobic performance parameters derived from the MART, which supports previous suggestions that both the aerobic and anaerobic energy systems are important for the performance of soccer-specific high-intensity intermittent exercise (Bangsbo 1994; Mohr et al. 2003). However, the post-training improvement in YIRT2 performance was only associated with the increase in the players' anaerobic fitness when expressed as anaerobic power, maximal speed attained, and time to exhaustion in the MART.

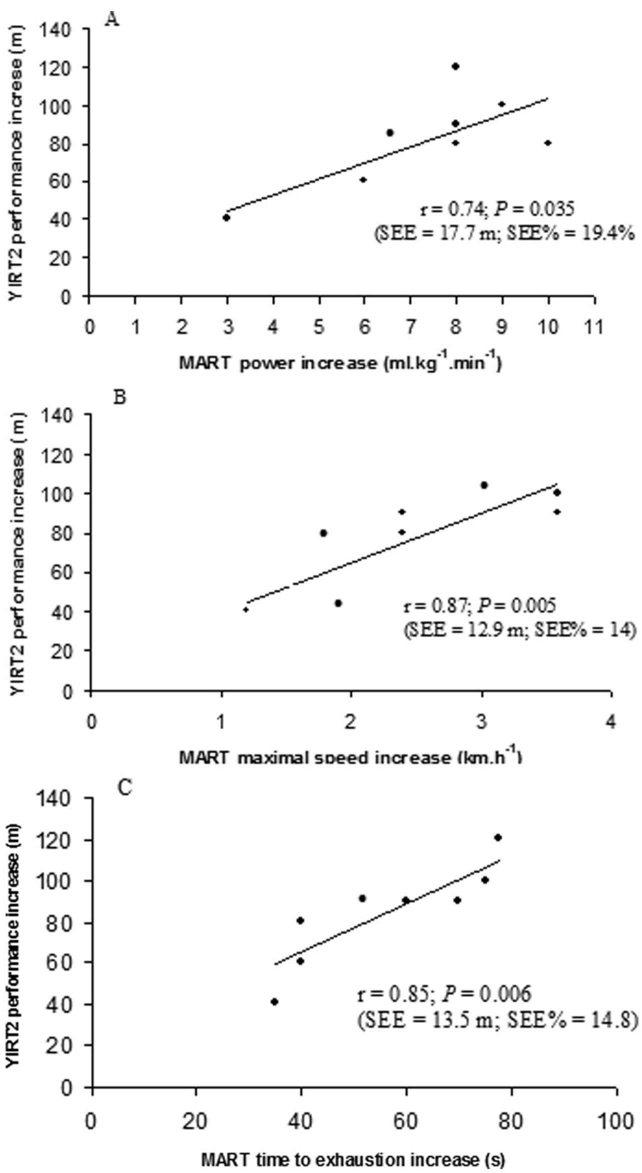
During the sub-maximal stages of the YIRT2, a high level of aerobic fitness will prevent reliance on anaerobic energy production and can potentially delay the onset of fatigue. However, as the intensity of the shuttle runs increase and exceed a player's $\dot{V}O_{2max}$, a large capacity for anaerobic energy production will be beneficial as it will enable a player to exercise for a sustained period at these supra-$\dot{V}O_{2max}$ running speeds (Reilly et al. 2000). Therefore, when soccer players are matched for aerobic fitness and $\dot{V}O_2$ kinetics, it is the players who possess a larger anaerobic capacity that will be capable of performing more high-intensity soccer-specific running. Analysis of HR measures taken during the YIRT2 supports this hypothesis. As the max HR values recorded during the YIRT2 (Table 5) were similar to those recorded at $\dot{V}O_{2max}$ during the incremental exercise test to exhaustion (Table 2), it can be assumed that $\dot{V}O_{2max}$ was attained in the YIRT2. Based on this association, HR data would indicate that although the TRA group reached $\dot{V}O_{2max}$ at the same stage of the YIRT2 before (720 m) and after (728 m) training, they were capable of running further at speeds above $\dot{V}O_{2max}$ after (259 m) than before (176 m) the intervention.

Table 5. Performance and physiological measures recorded from the YIRT2 and MART for the CON (n = 8) and TRA (n = 8) groups before and after the training intervention (mean ± SD).

	CON (n = 8)		TRA (n = 8)	
Measure	Before	After	Before	After
YIRT2 distance (m)	891±46	888±42	896±37	987±44**,##
YIRT2 HR max (beats·min⁻¹)	190±5	191±4	193±6	192±7
MART power (ml·kg⁻¹·min⁻¹)	113.1±5.1	112.6±5.7	115.2±4.0	124.2±5.2*,##
MART speed (km·h⁻¹)	22.3±1.0	22.6±1.4	22.4±1.2	24.6±1.1*,#
MART time (s)	170±16	172±16	167±18	184±16*,##
MART [Hla] mmol·l⁻¹)	17.6±1.3	16.7±1.7	17.2±1.2	17.4±1.4

Note: *Difference after the intervention within a group, p < 0.05; **Difference after the intervention within a group, p < 0.01; #Difference after the intervention for corresponding values between groups, p < 0.05; ##Difference after the intervention for corresponding values between groups, p < 0.01. (YIRT2, Yo-Yo Intermittent Recovery Test level 2; MART, maximal anaerobic running test; CON, control group; TRA, training group.)

Fig. 3. Panels A to C represent the significant correlations between improvements in Yo-Yo Intermittent Recovery Test Level 2 (YIRT2) performance and power (A), maximal running speed (B), and time to exhaustion for the training group (C) (n = 8).



These findings support Ramsbottom et al. (2001) who reported improved continuous high-intensity running capacity was associated with an increased anaerobic capacity without a change to $\dot{V}O_{2max}$. The decisive contribution made by the anaerobic energy system during high-intensity exercise could also help to explain the results of Krustrup et al. (2003) who reported increases in YIRT1 performance with no or only small changes in $\dot{V}O_{2max}$ after periods of high-intensity soccer-specific training.

The τ_{2on} of the CON group was significantly shorter than that of the TRA before the intervention (p = 0.031). Consequently, analysis revealed the CON group (916 ± 55 mL) to have a smaller (p = 0.039) phase III DO_2 than the TRA group (1009 ± 61 mL), although there was no difference in phase II (p = 0.195) or total (p = 0.218) DO_2 between groups. It is also arguable whether a difference of 93 mL in DO_2 between groups (10.2%) would be of physiological significance for soccer performance, as no difference in YIRT2 performance was observed between groups before the intervention. Following the intervention, the phase III DO_2 of the groups was similar as the τ_{2on} of the CON group lengthened considerably to a value similar to that of the TRA group. Such a change in a kinetic measure for the CON group was not expected and is possibly a result of the poor test–retest reproducibility that seems inherent in phase III measures. Furthermore, the lengthening in τ_2 of the CON group did not lead to a decrease in their YIRT2 performance. This supports the findings of the previous study by this group (Wells et al. 2012) that the speed of the slow component and, hence, DO_2 does not influence soccer-specific high-intensity running capacity in players matched for aerobic fitness.

Several adaptations within skeletal muscle have been associated with an increase in glycolytic capacity following a period of training. The metabolic enzymes that drive and regulate glycolysis have been reported to increase between 10% and 56% along with a concomitant improvement in high-intensity exercise performance following periods of high-intensity training (MacDougall et al. 1998; Roberts et al. 1982; Simoneau et al. 1985). The increase in glycolytic enzymes following a period of high-intensity training causes a change in the characteristics of the different muscle fibre types. It has been reported that high-intensity interval training similar to that performed in this study increases the glcolytic capabilities of type I fibres, instigating them to take on the characteristics of type IIa fibres (Boobis 1987; Jansson et al. 1990). The high force generation and rapid contraction time of type II fibres would also be beneficial for the large forces required in the performance of high- and maximal-intensity runs. In addition, type II fibres possess greater levels of the substrates required for anaerobic energy production (Sahlin et al. 1979). Soderlund and Hultman (1991) and Greenhaff et al. (1991) reported that PCr content could be 15% and 25% higher, respectively, in type II than type I fibres.

In summary, the findings of this study indicate that performance of elite soccer players in the YIRT2 significantly improved after 6 weeks of high-intensity intermittent training designed to increase soccer-specific high-intensity running capacity. The increase in YIRT2 was matched by an increase in anaerobic capacity as indicated by the MART and the change in the 2 measures was positively correlated. Although measures of aerobic fitness and $\dot{V}O_2$ kinetics were correlated with YIRT2, they were not observed to increase following the training. Consequently they were not correlated with the change in YIRT2.

These findings show that when soccer players are matched for aerobic fitness, it is the players who possess the largest anaerobic capacity that will be capable of performing the most high-intensity intermittent running (Edwards et al. 2003; Wells et al. 2012). The high-intensity and sporadic nature of YIRT2, where a player performs a high-intensity run every 10 s, would appear to be such that the $\dot{V}O_2$ kinetic responses of elite players do not substantially reduce anaerobic contributions to the onset of exercise or enhance recovery processes at exercise cessation. Further research is required to determine which of the physiological adaptations that accompany an increase in anaerobic capacity are responsible for the improvement in YIRT2 test performance. These findings could potentially have important implications for the way in which the fitness of soccer players is trained in the future.

There are relatively few opportunities during the competitive soccer season where concentrated periods of conditioning can be undertaken with the particular purpose of augmenting fitness rather than specifically preparing for an upcoming match. As the management of training load is vital to prevent injury and to ensure players remain in optimal physical condition, such meaningful adaptation to low-volume high-intensity running from 6 weeks of concentrated training is likely to be of considerable meaning to conditioning coaches and sports scientists working with professional soccer players. This may be achievable either in preseason or in-season at key stages. However it is recommended training load is monitored with either ratings of perceived exertion and (or) a global positioning system, the omission of which is a limitation to this study. Nevertheless, this study identifies that the addition of low-volume high-intensity running is of practical meaning if integrated into a multidisciplinary approach to player development where technical and tactical development are synergised with physical conditioning.

References

Bangsbo, J. 1994. Fitness training in football – a scientific approach. HO and Storm, Bagsvaerd.

Bangsbo, J., and Michalsik, L. 1993. Assessment of the physiological capacity of elite soccer players. *In* Science and Football II. *Edited by* T. Reilly, J. Clarys, and A. Stibbe. E. and F.N. Spon, London, pp. 53–60.

Boobis, L.H. 1987. Metabolic aspects of fatigue during sprinting. *In* Exercise Benefits, Limits and Adaptations. *Edited by* D.A.D. Macleod, R.J. Maughn, M. Nimmo, T. Reilly, and C. Williams. E. and F.N. Spon, London, pp. 116–143.

Clark, N.A., Edwards, A.M., Morton, R.H., and Butterly, R.J. 2008. Season-to-season variations of physiological fitness within a squad of professional male soccer players. J. Sports Sci. Med. **7**: 157–165. PMID:24150149.

Demarle, A.P., Slawinski, J.J., Laffite, L.P., Bocquet, V.G., Koralsztein, J.P., and Billat, V.L. 2001. Decrease of O_2 deficit is a potential factor in increased time to exhaustion after specific endurance training. J Appl. Physiol. **90**: 947–953. PMID:11181605.

Edwards, A.M., and Noakes, T.D. 2009. Dehydration: cause of fatigue or sign of pacing in elite soccer? Sports Med. **39**: 1–13. doi:10.2165/00007256-200939010-00001. PMID:19093692.

Edwards, A.M., Challis, N.V., Chapman, J., Claxton, D.B., and Fysh, M.L. 1999. Oxygen uptake kinetics determined by PRBS techniques differentiate elite endurance runners from elite sprinters. Int. J. Sports Med. **20**: 1–6. doi:10.1055/s-2007-971082. PMID:10090453.

Edwards, A.M., Clark, N., and Macfadyen, A.M. 2003. Lactate and gas exchange thresholds reflect the training status of professional soccer players where maximum aerobic power is unchanged. J. Sport Sci. Med. **2**: 23–29.

Edwards, A.M., Bentley, M.B., Mann, M.E., and Seaholme, T.S. 2011. Self-pacing in interval training: a teleoanticipatory approach. Psychophysiology, **48**: 136–141. doi:10.1111/j.1469-8986.2010.01034.x. PMID:20536904.

Greenhaff., P.L, Ren, J.M., Soderlund, K., and Hultman, E. 1991. Energy metabolism in single human muscle fibres during contraction without and with epinephrine infusion. Am. J. Physiol. **260**: E713–E718. PMID:2035627.

Helgerud, J., Engen, L.C., Wisloff, U., and Hoff, J. 2001. Aerobic endurance training improves soccer performance. Med. Sci. Sports Exerc. **33**: 1925–1931. doi:10.1097/00005768-200111000-00019. PMID:11689745.

Jansson, E., Dudley, G.A., and Norman, B. 1990. Relationship of recovery from intense exercise to the oxidative potential of skeletal muscle. Acta Physiol. Scand. **139**: 147–152. doi:10.1111/j.1748-1716.1990.tb08907.x. PMID:2356745.

Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steenberg, A., et al. 2003. The Yo-Yo intermittent recovery test: physiological response, reliability, and validity. Med. Sci. Sports Exerc. **35**: 697–705. doi:10.1249/01.MSS.0000058441.94520.32. PMID:12673156.

Krustrup, P., Mohr, M., Nybo, L., Nielsen, J., and Bangsbo, J. 2005. The Yo-Yo intermittent recovery test can be used to evaluate effects of intermittent exercise training regimes. *In* Proceedings of the 52nd Annual Meeting of the American College of Sports Medicine, Nashville, US, pp. 518.

MacDougall, J.D., Hicks, A.L., and MacDonald, J.R. 1998. Muscle performance and enzymatic adaptations to interval sprint training. J. Appl. Physiol. **84**: 2138–2142. PMID:9609810.

Mohr, M., Krustrup, P., and Bangsbo, J. 2003. Match performance of high-standard soccer players with special reference to the development of fatigue. J. Sports Sci. **21**: 519–528. doi:10.1080/0264041031000071182. PMID:12848386.

Mohr, M., Krustrup, P., Kirkendal, D., and Bangsbo, J. 2008. Match activities of elite women soccer players at different performance levels. J. Strength Cond. Res. **22**. 341–349. doi:10.1519/JSC.0b013e318165fef6. PMID:18550946.

Nevill, M.E., Boobis, L.H., and Brooks, S. 1989. Effect of training on muscle metabolism during treadmill sprinting. J. Appl. Physiol. **67**: 2376–2382. PMID:2606844.

Nummela, A., Mero, A., Stray-Gundersen, J., and Rusko, H. 1996. Important determinants of anaerobic running performance in male athletes and non-athletes. Int. J. Sports Med. **17**: S91–S96. doi:10.1055/s-2007-972907. PMID: 8844271.

Özyener, F., Rossiter, H., Ward, S.A., and Whipp, B.J. 2001. Influence of exercise intensity on the on- and off-transient kinetics of pulmonary oxygen uptake in humans. J Physiol. (Lond.), **533**: 891–902. doi:10.1111/j.1469-7793.2001.t01-1-00891.x. PMID:11410644.

Ramsbottom, R., Nevill, M.E., Seager, R.D., and Hazeldine, R. 2001. Effect of training on accumulated oxygen deficit and shuttle run performance. J. Sports Med. Phys. Fitness, **41**: 281–290. PMID:11533556.

Reilly, T., Bangsbo, J., and Franks, A. 2000. Anthropometric and physiological predispositions for elite soccer. J. Sports Sci. **18**: 669–683. doi:10.1080/02640410050120050. PMID:11043893.

Roberts, A.D., Billeter, R., and Howald, H. 1982. Anaerobic muscle enzyme changes after interval training. Int. J. Sports Med. **3**: 18–21. doi:10.1055/s-2008-1026055. PMID:7068292.

Sahlin, K., Harris, R.C., and Hultman, E. 1979. Resynthesis of creatine phosphate in human muscle after exercise in relation to intramuscular pH and availability of oxygen. Scand. J. Clin. Lab. Invest. **39**: 551–558. doi:10.3109/00365517909108833. PMID:43580.

Simoneau, J.A., Lortie, G., and Boulay, M.R. 1985. Human skeletal muscle fibre type alteration with high-intensity intermittent training. Eur. J. Appl. Physiol. **54**: 250–253. doi:10.1007/BF00426141. PMID:4065109.

Soderlund, K., and Hultman, E. 1991. ATP and phosphocreatine changes in single human muscle fibres after intense electrical stimulation. Am. J. Physiol. **261**: E737–E741. PMID:1767834.

Van Gool, D., Van Gervan, D., and Boutsman, J. 1988. The physiological load imposed on soccer players during real match-play. *In* Science and Football. *Edited by* T. Reilly, A. Lees, K. Davids, and W.J. Murphy. E and F.N. Spon, London, pp. 51–59.

Wells, C.M., Edwards, A.M., Winter, E.M., Fysh, M.L., and Drust, B. 2012. Sport-specific fitness testing differentiates professional from amateur soccer players where $\dot{V}O_{2max}$ and $\dot{V}O_2$ kinetics do not. J. Sports Med. Phys. Fitness, **52**: 245–254. PMID:22648462.