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The Effect of Constant-Intensity Endurance Training and High-Intensity Interval Training on Aerobic and Anaerobic Parameters in Youth

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Abstract

Introduction: High-Intensity Interval Training (HIIT) and Constant-Intensity Endurance Training (CIET) improves peak oxygen uptake ($\dot{V}O_2$) similarly in adults; but in children this remains unclear, as does the interaction with maturity. *Methods*: Thirty-seven boys formed three groups: HIIT (football; n = 14; 14.3 ± 3.1 years), CIET (distance runners; n = 12; 13.1 ± 2.5 years) and a control (CON) group (n = 11; 13.7 ± 3.2 years). Peak $\dot{V}O2$ and gas exchange threshold (GET) were determined from a ramp test with anaerobic performance quantified using a 30 m sprint pre-and-post a three-month training cycle. Maturation was assessed using maturity offset equations. *Results*: The HIIT groups peak $\dot{V}O_2$ was significantly higher than the CON group pre (peak $\dot{V}O2$: 2.54±0.63 $l·min^{-1}$ vs 2.03±0.53 $l·min^{-1}$, d = 0.88; GET: 1.41±0.26 $l·min^{-1}$ vs 1.13±0.29 $l·min^{-1}$, d = 1.02) and post-training (peak $\dot{V}O2$: 2.63±0.73 $l·min^{-1}$ vs 2.08±0.64 $l·min^{-1}$, d = 0.80; GET: 1.32±0.33 $l·min^{-1}$ vs 1.15±0.38 $l·min^{-1}$, d = 0.48). All groups showed a similar magnitude of change over the three-month training period ($p>0.05$). *Conclusion:* HIIT was not superior to CIET for improving aerobic or anaerobic parameters in adolescents. Secondly, pre- and post-pubertal participants demonstrated similar trainability, highlighting no maturity and training interaction.

Keywords

Peak $\dot{V}O_2$; Maturity; Adolescence; Peak Power; pre-pubertal; pubertal

Introduction

In recent years, there has been a growing focus on long-term athlete development (LTAD) programs to prepare children and adolescents for optimised sports performance and a physically active lifestyle (Pichardo, Oliver, Harrison, Maulder, & Lloyd, 2018). Within these increasingly utilised LTAD models, the primary focus is on two key types of training: high-intensity interval training (HIIT) and continuous-intensity exercise training (CIET; Pichardo et al., 2018). Constant-intensity exercise training improves maximal aerobic capacity (peak $\dot{V}O_2$) in youth through central mechanisms, including an increased cardiac output ($\dot{Q}$) and stroke volume (SV; Armstrong, 2015; Obert et al., 2003). Additionally, sub-maximal parameters, including the gas exchange threshold (GET; Hebestreit, Staschen, & Hebestreit, 2000), lactate threshold (LT; Matos & Winsley, 2007; Pitt et al., 2015), and oxygen uptake kinetics (Armstrong & Barker, 2009; Lai et al., 2008; Marwood, Roche, Rowland, Garrard, & Unnithan, 2010), are also postulated to demonstrate significant training effects in youth.

More recently, high-intensity interval training (HIIT), which aims to improve peak $\dot{V}O_2$ and anaerobic performance by similar magnitudes to CIET but with significantly less training time, has received an increased interest in the paediatric population. Indeed, Buchan et al. (2015) demonstrated that HIIT can elicit similar reductions in cardiovascular disease (CVD) risk factors to that of CIET in 15% of the time. Additionally, Sperlich et al. (2014) reported that only HIIT significantly improved peak $\dot{V}O_2$ and 1,000m running performance in football players (13.5 ± 0.4 years), despite engaging in approximately 50% less total exercise time than a CIET group over a 5-week intervention. High-intensity interval training increases muscular oxidative capacity and hypervolemia, facilitating an increased SV during exercise (Rowland, 2009). Thus, peak $\dot{V}O_2$ and anaerobic performances are shown to concomitantly increase. Nevertheless, HIIT research remains in its infancy in paediatric populations, which is surprising given its potential merits in children in whom the apparent immaturity of the glycolytic energy system enables a quicker recovery from near-maximal bouts of exercise (Hebestriet, Mimura, & Bar-Or, 1993), and the apparent lesser training stimulus needed to elicit similar, if not greater, improvements than CIET methods (Sperlich et al. 2014).

In recent years, LTAD programs have highlighted the importance of accounting for the maturation of the athletes concerned and not just their chronological age (Armstrong, 2007; Lloyd & Oliver, 2012). During puberty, high levels of androgenic hormones are present to facilitate normal growth and development (Farr, Laddu, & Going, 2014). However, these androgenic hormones, when exogenously supplemented in adults, have been shown to have significant and pronounced performance effects (Doessing & Kjaer, 2005). Subsequently, Katch (1983) proposed that there may be a 'maturational threshold' or 'trigger point' during puberty where responses to training are increased, mediated by increases in androgenic hormones. It has been postulated that there may be a 'window of opportunity' for 1-3 years surrounding peak height velocity (PHV) where performance improvements in peak $\dot{V}O_2$, strength and power can be increased by a greater magnitude than seen pre-PHV (Rowland, 1997).

Despite the theoretical argument for the possible presence of a maturational threshold, there is little empirical evidence to support it in HIIT and CIET-based activities (Cunha et al., 2011; Cunha et al., 2016). This may be due to methodological limitations, such as the paucity of longitudinal studies tracking children across all maturation stages and the absence of control groups enabling the concomitant process of growth and maturation to be accounted for (Barker, Day, Smith, Bond, & Williams, 2014). Conversely, although adolescents may experience increased levels of androgenic hormones that could potentially increase trainability, it is predicted that 98.0 – 99.8% of testosterone is bound to proteins within the blood and utilised for various functions relating to growth and sexual maturation (Vingren et al., 2010). This leaves only 0.2 – 2.0% of circulating testosterone ‘free’ to potentially initiate an androgenic response to a training stimulus (Vingren et al., 2010), which may explain why previous studies demonstrated no significant interactions between training adaptations, sexual maturation and growth (Baxter-Jones et al. 1993; McNarry et al. 2014). Nevertheless, despite these concerns, and lack of empirical evidence, increasing numbers of NGB’s have embedded the maturational threshold hypothesis into their LTAD programs (Lloyd & Oliver, 2012).

A key methodological limitation of many studies to date is their reliance on strictly controlled, laboratory-based training protocols, which lack ecological validity and cannot be easily transferred to a habitual training environment. Therefore, the aim of this study was to compare the effect of a habitual HIIT and CIET-based training cycle on aerobic and anaerobic performance in children and adolescents and to compare the magnitude of any training-induced adaptations elicited to investigate whether a maturational threshold was manifest.

Methods

Participants

Forty-four healthy boys aged 8 – 18 years from schools and local sports clubs in the East Midlands, England, provided parental/guardian and child consent and assent, respectively, to participate in this observational study. Following participant attrition due to injuries (n = 2), lack of time or desire to finish the study (n = 4) and a wish to rest before a major competition at the weekend (n = 1), the final sample size consisted of 37 participants (CIET = 12, HIIT = 14, Control (CON) = 11). All participants were allocated to groups according to their pre-selected sport. Ethical approval was obtained from the A-STEM Ethics Committee at Swansea University and the study conformed to the Declaration of Helsinki.

To investigate HIIT and CIET, participants were recruited from local football and running clubs, respectively. Specifically, participants in the HIIT and CIET groups both completed 6.5 ± 3.5 hours of structured training and competitions a week within their sports clubs. A typical training session for the HIIT group included football-specific drills and small-sided games, concluding in a full game for the last 15 minutes of the session. In contrast, a typical CIET session consisted of a warm-up period, running drills and ending with an approximately 30-minute main session of continuous running at alternating speeds. All participants in the CIET group were 3000m and 5000m specialists on the track. During the training-cycle observed, they were building their endurance base for the track season, with a typical session involving approximately 8000m in approximately 40 minutes. All training sessions were supervised by professional coaches at respective clubs. All participants had been training for at least 6 months within their clubs prior to study entry. The control group comprised of healthy children that performed no extracurricular physical activity outside of mandatory physical education (PE) lessons within school.

Experimental Protocol

Participants in the HIIT and CIET groups were assessed pre and post a periodised three-month training cycle. Specifically, the HIIT group were training for performance in the final league fixtures and domestic cup competitions. The CIET athletes were monitored in the lead up to the county championships, a key point in the season where athletes peak for selection to national competitions.

Standing and sitting stature and body mass were assessed using a stadiometer (Holtain, Crymych, Dyfed, UK) and electronic scales (Seca 803, Seca, Chino, CA, USA), accurate to the nearest 0.1 cm and 0.1 kg, respectively. Body mass index (BMI) was subsequently calculated using the standard formula; body mass / height^2 (kg·m^2). Maturation was subsequently assessed using the maturity offset equations of Mirwald et al. (2003). Thresholds of ≤ -1 years before PHV, ≥ -0.99 years PHV to ≤ +0.99 years PHV and ≥ +1 years PHV were used to classify participants as pre-pubertal, pubertal and post-pubertal, respectively.

Peak $\dot{V}O_2$ assessment

Participants completed an incremental ramp protocol on a treadmill to volitional exhaustion, which involved a 2-minute warm-up at 5 km·h^{-1} after which the speed increased by 1 km·h·min^{-1}, with a gradient of 1% (Jones & Carter, 2000). When maximal running speed was achieved, defined as the highest comfortable speed that was able to be maintained by the participant, the gradient of the treadmill was subsequently increased by 1% every minute until exhaustion was reached. Both gas exchange and heart rate were measured on a breath-by-breath basis throughout the test (Oxycon Mobile, CareFusion, Leibnizstrasse, Germany).

Anaerobic Capacity Assessment

Running anaerobic capacity was measured through a novel field-based measure recently developed by Samozino et al. (2016), which assesses peak power (PP) and velocity (m·s^{-1}) during an over-ground 30m sprint using basic anthropometric measurements of height (cm) and body mass (kg). Before undertaking the sprint protocol, all children and adolescents participated in a standardised 5-minute low-intensity running warm-up with all participants completing one 30m sprint at the end of the warm-up, acting as a familiarisation trial. Subsequently, participants conducted three sprints from a standing start to ensure the vertical displacement during the sprint was minimised (Samozino et al., 2016), with at least two minutes between each sprint. Only the fastest trial was carried forward for analysis purposes. A STALKER ATS II radar gun (STALKER RADAR, Plano, Texas, USA) was mounted on a tripod and positioned 10m directly behind the participants to record the raw velocity of the participants over the 30m period at a rate of 46.875 Hz. Force-velocity-power (F-v-P) profile derived variables were shown to have at least moderate reliability in paediatric populations (ICC: 0.50 – 0.88; CV: 1.6 – 9.5%; Runacres et al. *under review*)

Physical Activity Assessment

To account for physical activity levels, an ActiSleep+ Accelerometer (ActiGraph, Pensacola, Florida, USA) recording at 100 Hz was worn on the right hip for seven consecutive days. A log was provided to monitor removal periods and the reasons to aid with more detailed analyses. Consistent with recent paediatric research, a wear-time criterion of ≥8 hours on at least two weekdays and one weekend day was used (Troiano et al., 2008) to maximise data inclusion within the analysis. Non-wear time was classified as 20 consecutive minutes with zero counts (Migueles et al., 2017). All data was downloaded in one second epochs to avoid the misclassification of epoch intensity using KineSoft (Version 3.3.75, New Brunswick, Canada) and in the absence of a universal consensus to classify activity intensity, Evenson cut-points were used (Evenson, Catellier, Gill, Ondrak, & McMurray, 2008). The mean amount of time spent in each intensity was calculated per day and across the week, accounting for wear-time according to self-reported log-sheets.

Data Analyses

To account for body size, the $\dot{V}O_2$ data was allometrically scaled using the methods reported elsewhere (McNarry, Mackintosh, & Stoedefalke, 2014). The GET was computed using the V-slope method (Beaver, Wasserman, & Whipp, 1986), and defined as the point at which carbon dioxide ($\dot{V}CO_2$) rose disproportionally to $\dot{V}O_2$. The raw $\dot{V}O_2$ was interpolated to 10 second intervals and peak $\dot{V}O_2$ was determined as the highest stationary average within the last two minutes of the test. The raw data from the STALKER ATS radar gun was modelled with a mono-exponential curve to produce a horizontal velocity (Vh) - time (t) profile (Samozino et al. 2016). This function was then integrated to obtain the acceleration, $\alpha_H(t)$, of the body's centre of mass (COM), with the assumption that the human body can be modelled as a complete system represented by its COM. The fundamental laws of dynamics were then applied to calculate the net horizontal antero-posterior force, $F_H(t)$, applied to the COM over time (Samozino et al., 2016). This was estimated from aerodynamic drag using stature (cm), body mass (kg) and fixed drag coefficients (Samozino et al., 2016). The power output applied in the antero-posterior direction (P_H) was then subsequently modelled, assuming the force applied in the vertical direction is quasi-null during over-ground sprinting.

Statistical Analysis

All descriptive statistics are presented as mean ± standard deviation unless otherwise stated. Statistical analyses were conducted using the SPSS Statistics Software Package version 22 (IBM SPSS, IBM, Armonk, NY, USA), with significance accepted at $p < 0.05$. A two-way mixed ANOVA with repeated measures was conducted for each variable to analyse training and maturity effects and their interaction. Subsequent posthoc analyses were performed with Bonferroni correction, when appropriate, to identify where significant differences occurred. Cohens *d* was also calculated with ≤ 0.20, ≥ 0.21 - ≤ 0.60, ≥ 0.61 - ≤ 0.80, and ≥ 0.81 considered a trivial, moderate, large and very large effects, respectively.

Results

Anthropometrics

Between group analyses revealed the CIET group had a significantly lower BMI than the HIIT group, irrespective of time ($F_{(2,35)} = 4.90$; $p < 0.02$, $d = 1.35$; Table 1). The CIET and HIIT group performed significantly more moderate-to-vigorous physical activity than the control group, regardless of time-point ($F_{(2,35)} = 8.12$, $p < 0.04$, d = 0.62), but there was no difference between the HIIT and CIET groups at either time-point (p > 0.05, d = 0.12). All other anthropometric variables were matched between all groups at baseline (p > 0.05). There was a significant increase in height, body mass and BMI across time in all participants ($p < 0.01$, $d = 0.86$). Any participant which changed maturity status with these increases in anthropometric measurements (of which there were 2) were still included within the original maturity classification for analyses.

Influence of Training

$\dot{V}O_2$ peak ($l \cdot min^{-1}$) and allometrically-scaled peak $\dot{V}O_2$ ($ml \cdot kg^{-b} \cdot min^{-1}$) significantly improved pre- to post-training in all participants, irrespective of training status or maturity (peak $\dot{V}O_2$: $F_{(1,29)} = 8.91$, $p < 0.01$, $d = 0.23$; scaled peak $\dot{V}O_2$: $F_{(1,29)} = 55.86$, $p < 0.01$ $d = 0.96$). The HIIT group demonstrated a significantly higher absolute peak $\dot{V}O_2$ ($F_{(2,29)} = 4.29$, $p < 0.02$, $d = 0.76$) and GET ($F_{(2,29)} = 3.27$, $p < 0.02$, $d = 0.96$) in comparison to the CON group at baseline and post-training, with no differences between any other training group at either time-point ($p > 0.05$). The magnitude of change in the GET was significantly greater in the CIET than HIIT group (*d* = 0.92), with no other significant differences found between groups. Furthermore, neither relative peak $\dot{V}O_2$ ($ml \cdot kg \cdot min^{-1}$; $F_{(1,29)} = 0.73$, $p > 0.40$) nor GET in relative terms (% peak $\dot{V}O_2$; $F_{(1,29)} = 0.14$, $p > 0.71$) differed from baseline to post-training [Table 2].

In terms of anaerobic performance, at baseline the CON group had a significantly higher maximum velocity (V_{max}) than the HIIT group (*d* = 0.91) and a faster mean velocity (MV) and 30m sprint time (*d* = 0.85) at baseline. However, after the three-months of training there was no significant difference between the HIIT and CON groups ($p > 0.05$). There was no training effect for any other anaerobic variable over the three-month training cycle ($p > 0.05$).

Influence of Maturation

Pre-pubertal children demonstrated lower absolute peak $\dot{V}O_2$ than pubertal ($p < 0.01$, *d* = 2.08) and post-pubertal participants ($p < 0.01$, *d* = 2.48) both pre- and post-training whilst no difference was evident between the pubertal and post-pubertal groups ($p > 0.64$, *d* = 0.11). Relative GET was higher in pre- than post-pubertal participants ($p < 0.05$, *d* = 1.64). No significant influence of maturity was observed on relative $\dot{V}O_2$ peak ($F_{(2,29)} = 2.39$, $p > 0.11$) or scaled peak $\dot{V}O_2$ ($F_{(2,29)} = 1.17$, $p > 0.33$) at either time-point.

Pre-pubertal children had a significantly lower peak power (PP) and mean power (MP) than pubertal (PP: $p < 0.05$ *d* = 1.34; MP: $p < 0.05$, *d* = 0.67) and post-pubertal participants (PP: $p < 0.01$ *d* = 1.39; MP: $p < 0.01$ *d* = 1.14), with pubertal participants also showing a significantly lower PP than post-pubertal participants ($p < 0.01$, *d* = 0.54) at both baseline and post-training. However, there were no significant differences in MP between pubertal and post-pubertal participants ($p > 0.05$, $d = 0.02$). There was no maturational effect on any other anaerobic parameter at either time-point.

****INSERT TABLE 1 NEAR HERE****

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Discussion

The aim of the current study was to observe the effect of a three-month training cycle on aerobic and anaerobic parameters in youth athletes to ascertain whether habitual CIET or HIIT engendered greater changes. Furthermore, this study aimed to assess the influence of maturity status on aerobic and anaerobic performance. The main findings of this study were that neither a habitual HIIT nor CIET training cycle elicited significant improvements in aerobic or anaerobic performance in previously trained children and adolescents.

Influence of Training – Aerobic Parameters

Converse to the large body of literature which argues HIIT elicits a greater peak $\dot{V}O_2$ improvement than traditional CIET, the present study found similar improvements after CIET and HIIT (+0.19 $l \cdot min^{-1}$ vs 0.14 $l \cdot min^{-1}$, $d = 0.18$) respectively. The findings of the present study are consistent with several training studies that refute HIIT having a greater efficacy than CIET in eliciting aerobic performance enhancements in youth (Cunha et al., 2011; Cunha et al., 2016). However, Logan, Harris, Duncan, & Schofield (2014) reported that when CIET and no-exercise CON groups were compared to HIIT interventions, HIIT elicited a 4% and 10% greater improvement, respectively. Conversely, a meta-analysis focused on the effects of HIIT on health-related fitness reported a mean improvement of 2.6 $ml \cdot kg \cdot min^{-1}$ (95% Confidence Intervals: 1.8 – 3.3

ml·kg·min^{-1}; Costigan, Eather, Plotnikoff, Taaffe, & Lubans, 2015), equivalent to approximately 3%, when compared to moderate-intensity interventions and no-exercise control groups. Whilst the present study showed similar improvement in the HIIT group over the course of the three-month intervention (~2.6%), there was no significant difference compared to the CIET or CON groups. Such discrepancies may be explained by the paucity of large studies included within the reviews, the specialised populations often involved within studies of this type, and the lack of control over the training implemented by the coaches. These may collectively limit the generalisability to the wider adolescent population. Whilst both reviews concluded the longer and more frequent the intervention, the greater the training response observed, further research is warranted to confirm this postulation.

Sperlich et al. (2011) investigated the effect of a 5-week HIIT versus CIET program in 19 male football players. The HIIT group performed exercise at the equivalent of ~90% max heart rate, whereas the CIET group exercised at 60 - 75% max HR. After the 5-week intervention, peak $\dot{V}O_2$ only improved in the HIIT group (+3.8 ml·kg·min^{-1}) compared to a non-significant (1.1 ml·kg·min^{-1}) increase after CIET, which is contradictory to the present study. Such discrepancies may be related to the type of HIIT intervention utilised as an intensity of > 85% max HR has been proposed as the threshold beyond which significant peak $\dot{V}O_2$ improvements will be elicited when total work is controlled for (Massicotte & Macnab, 1974; Mucci et al., 2013). Given the ecological nature of the study design, the HIIT participants in the current study may not have been exercising at a sufficient intensity to demonstrate similar significant improvements. Furthermore, previous research utilising HIIT focused on previously untrained adolescents and failed to account for habitual physical activity levels, potentially exaggerating the effectiveness of HIIT in this population (Costigan et al., 2015).

Influence of Training – Anaerobic Parameters

Anaerobic trainability has received substantially less attention than aerobic trainability in youth due to the lack of consensus over the best measurement method and researchers viewing anaerobic capacity as a performance rather than a health-based measure (McNarry & Jones, 2014). The paucity of well-designed, controlled studies in this area makes it difficult to state whether training enhances anaerobic performance beyond the levels associated with growth and maturation.

McNarry & Jones (2014) highlighted the wide discrepancies between training studies, with results ranging from negligible up to ~20% improvement in anaerobic performance. The training type (HIIT or CIET) was not reported to be associated with the magnitude of anaerobic improvements (McNarry & Jones, 2014), agreeing with the present study with similar PP, MP, V_{max} and mean velocity (MV) improvements between groups. The wide discrepancies in PP and MP in the literature could be a result of differences in training protocols, participant characteristics and power assessment methods (Welshman & Armstrong, 1996). Specifically, some studies have utilised running-based interventions but subsequently tested anaerobic performance using a cycling wingate (WnT) (Armstrong, 2007; Armstrong, Barker, & McManus, 2015). Therefore, while the WnT may reveal increases in PP and MP, the transferability of these changes to V_{max} and sprinting performance is unknown. Thus, these studies have limited practical implications to running-based activities (Van Praagh, 2000).

Interaction of training and maturity

Given the similar response to habitual training demonstrated in the pre-pubertal children to pubertal and post-pubertal adolescents, the present study suggests that there is no maturational threshold. These findings therefore support the growing body of evidence suggesting that the current structure of LTAD programs may require revision as pre-pubertal children can display similar levels of trainability to post-pubertal adolescents (Baxter-Jones, Goldstein, & Helms, 1993; McNarry et al., 2014). This may be a result of the lack of available circulating testosterone during the adolescent growth spurt, with only up to 2% of total testosterone available at any one time (Vingren et al., 2010), to potentially produce androgenic effects to training stimuli. Furthermore, studies incorporating allometric scaling have reported no significant differences between maturity groups (Cunha et al., 2011; Cunha et al., 2016; McNarry et al., 2014), suggesting that when maturity is appropriately accounted for there is no significant difference between maturational stages.

Maximal velocity, average velocity and 30m-sprint time were unaffected by maturity in the present study, contradicting most of the paediatric literature (Meyers, Oliver, Hughes, Cronin, & Lloyd, 2015; Van Praagh, 2000). Rumpf, Cronin, Oliver, & Hughes, (2015) examined kinematic and kinetic parameters of maximum running speed across maturity and found significant increases with advancing maturation accredited to an increasing stride length and frequency. Conversely, Meyers et al. (2015) reported significant differences in V_{max} and MV between pre- and post-pubertal participants, with no differences between pre-pubertal and pubertal participants. However, it is pertinent to note that both studies investigated running velocity on a treadmill with only one familiarisation trial (Meyers et al., 2015; Rumpf et al., 2015). Indeed, previous research has advocated that pre-pubertal children require a more robust familiarisation than participants of greater maturity (McNarry & Jones, 2014). Therefore, it could be postulated that the pre-pubertal children's performance may not only have been enhanced with a more robust familiarisation protocol but potentially ameliorates the significant effects reported (Meyers et al., 2015; Rumpf et al., 2015).

Whilst there are numerous strengths associated with the current study, there are inevitably limitations that must be considered. Firstly, the low sample size makes it difficult to extrapolate these findings to the general population, with the low percentage of participants classified as pre-pubertal (15%) precluding strong inferences. Whilst the study was designed to maximise ecological validity, it is possible that the respective groups may not have performed their predominant training types in isolation. Specifically, the long-distance runners may have completed interval sessions and, similarly, the football players may have completed low-intensity fitness sessions. Nonetheless, long-distance runners and football players predominantly conform to the characteristics of CIET and HIIT, respectively (Armstrong, Tomkinson, & Ekelund, 2011; Hill-Haas, Dawson, Impellizzeri, & Coutts, 2011). Finally, it is noteworthy that all participants in the training groups had been undertaking regular training for at least 6 months prior to inclusion within the study, and it could therefore be postulated that they could already have exhibited some training effects prior to study commencement. Indeed, baseline fitness levels have been demonstrated to significantly influence the magnitude of responses reported from a training stimulus, thus if monitoring was conducted from initial engagement significant differences may have been observed (Armstrong, 2015; McNarry & Jones, 2014).

Summary & Conclusions

The present study provides evidence that HIIT may not be a more advantageous training tool than traditional CIET in this population. Future research should seek to ascertain whether a combination of both training types would elicit greater physiological adaptations than each in isolation. Furthermore, evidence is provided that refutes the maturational threshold hypothesis for HIIT and CIET based activities, but this should be interpreted with caution given the small sample size used within the current study.

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Declaration of Interest

The authors report no conflict of interest

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Table 1 – Participant characteristics at baseline and post 3-month training cycle

		Baseline			Post-	
		HIIT	**CIET**	**CONTROL**	**HIIT**	**CIET**
Participant Numbers	Pre-Pubertal	5	0	3	4	0
	Pubertal	6	9	6	6	8
	Post-Pubertal	5	6	4	4	4
Age (yrs)	Pre-Pubertal	9.0 ± 1.0	-	8.5 ± 0.7	9.0 ± 1.0*	-
	Pubertal	14.7 ± 1.0[a]	12.1 ± 0.8[a]	13.4 ± 2.0[a]	14.9 ± 1.1*	12.3 ± 0
	Post-Pubertal	17.3 ± 0.5[a,b]	17.3 ± 0.6[a,b]	18.0 ± 0.0[a,b]	17.3 ± 0.5*	18 ± 1.
Height (cm)	Pre-Pubertal	138.5 ± 3.6	-	135.6 ± 1.2	140.3 ± 3.5**	-
	Pubertal	163.9 ± 4.5[a]	159.5 ± 7.6[a]	156.7 ± 6.8[a]	164.9 ± 4.0**	161.4 ± 8
	Post-Pubertal	169.8 ± 6.6[a,b]	176.8 ± 6.5[a,b]	180.8 ± 1.2[a,b]	170.7 ± 5.7**	178.8 ± 5
Weight (kg)	Pre-Pubertal	34.7 ± 3.2	-	31.5 ± 0.6	36.4 ± 3.5**	-
	Pubertal	57.4 ± 7.0[a]	44.3 ± 5.0[a]	51.4 ± 8.9[a]	58.6 ± 7.1**	46.0 ± 5
	Post-Pubertal	65.1 ± 4.9[a,b]	60.7 ± 8.4[a,b]	64.8 ± 0.8[a,b]	66.1 ± 4.9**	62.9 ± 6
BMI ($kg \cdot m^2$)	Pre-Pubertal	18.0 ± 0.9[#]	-	17.1 ± 0.0	18.4 ± 1.1*[#]	-
	Pubertal	21.3 ± 2.3[a,#]	17.4 ± 1.9[a]	21.1 ± 4.4[a]	21.5 ± 2.4*[#]	17.7 ± 2
	Post-Pubertal	22.6 ± 1.4[a,#]	19.5 ± 3.3[a]	19.9 ± 0.5[a]	22.7 ± 1.6*[#]	19.8 ± 2
Maturity Offset (yrs)	Pre-Pubertal	-3.21 ± 0.73	-	-4.08 ± 0.14	-3.04 ± 0.72**	-
	Pubertal	-0.23 ± 0.57[a]	0.53 ± 0.66[a]	0.89 ± 1.45[a]	0.18 ± 0.67**	0.56 ± 1.
	Post-Pubertal	3.91 ± 0.61[a,b]	4.72 ± 0.54[a,b]	5.44 ± 0.52[a,b]	3.97 ± 0.45**	5.34 ± 0.

All values presented as mean ± SD, BMI = Body Mass Index

*Significant difference from baseline to post-intervention within groups at the p = 0.05 confidence interval

** Significant difference from baseline to post-intervention within groups at the p = 0.01 confidence interval

[a] Significant difference compared to pre-pubertal children within time-point

[b] Significant difference between pubertal and post-pubertal adolescents within time-point

[#] Significant difference between HIIT and CIET groups

Table 2 – Baseline and post-training cycle aerobic and anaerobic performances

		Baseline			Post traini
		HIIT	CIET	CONTROL	HIIT
$\dot{V}O_2$ Peak ($l \cdot min^{-1}$)	Pre-Pubertal	1.66 ± 0.69	-	1.41 ± 0.36	1.75 ± 0.19*
	Pubertal	2.60 ± 0.59 [a]	2.14 ± 0.22 [a]	2.18 ± 0.54 [a]	2.67 ± 0.69*
	Post-Pubertal	2.93 ± 0.23 [a]	2.31 ± 0.55 [a]	2.12 ± 0.12 [a]	3.21 ± 0.33*
Relative $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	Pre-Pubertal	48.1 ± 4.4	-	44.8 ± 12.2	48.3 ± 5.2
	Pubertal	45.3 ± 5.9	48.9 ± 7.5	42.7 ± 9.1	45.3 ± 8.3
	Post-Pubertal	45.1 ± 1.7	38.2 ± 8.4	32.7 ± 1.3	48.5 ± 4.0
Scaled $\dot{V}O_2$ ($ml \cdot kg^{-b} \cdot min^{-1}$)	Pre-Pubertal	85.2 ± 6.6	-	78.2 ± 21.2	97.7 ± 9.9*
	Pubertal	86.7 ± 13.1	90.1 ± 12.7	80.6 ± 17.2	100.6 ± 19.5*
	Post-Pubertal	88.7 ± 3.5	74.2 ± 16.0	64.1 ± 2.9	110.3 ± 8.9*
GET ($L \cdot min^{-1}$)	Pre-Pubertal	1.10 ± 0.18	-	0.77 ± 0.23	0.91 ± 0.30
	Pubertal	1.45 ± 0.26 [a]	1.19 ± 0.13 [a]	1.29 ± 0.19 [a]	1.36 ± 0.25
	Post-Pubertal	1.53 ± 0.10 [a]	1.14 ± 0.30 [a]	0.94 ± 0.16 [a]	1.58 ± 0.30
Relative GET (% $\dot{V}O_2$ Peak)	Pre-Pubertal	64.8 ± 11.5	-	54.1 ± 2.7	55.2 ± 1.3
	Pubertal	56.4 ± 4.5	55.6 ± 3.3	61.4 ± 14.8	49.9 ± 5.7
	Post-Pubertal	52.2 ± 1.8 [a]	49.4 ± 3.7 [a]	43.3 ± 4.1 [a]	49.8 ± 8.9
			ANAEROBIC PERFORMANCE		
Time to Peak Power (s)	Pre-Pubertal	0.36 ± 0.10	-	0.43 ± 0.06	0.68 ± 0.24*
	Pubertal	0.58 ± 0.12	0.49 ± 0.15	0.56 ± 0.08	0.75 ± 0.09*
	Post-Pubertal	0.56 ± 0.16	0.52 ± 0.14	0.65 ± 0.07	0.60 ± 0.36*
PP (W)	Pre-Pubertal	601.6 ± 152.4	-	524.5 ± 85.1	552.3 ± 356.5
	Pubertal	692.8 ± 78.7 [a]	754.8 ± 202.1 [a]	798.9 ± 158.4 [a]	691.0 ± 174.2
	Post-Pubertal	1001.0 ± 474.6 [a,b]	947.4 ± 192.4 [a]	874.8 ± 66.3 [a]	1099.9 ± 485.4
Relative PP ($W \cdot Kg^{-1}$)	Pre-Pubertal	17.2 ± 3.6	-	16.7 ± 3.0	15.1 ± 9.2
	Pubertal	12.2 ± 2.3	17.0 ± 4.4	15.9 ± 4.5	11.9 ± 3.1
	Post-Pubertal	15.5 ± 8.0	15.1 ± 2.9	13.4 ± 0.9	16.9 ± 8.1

MP (W)	Pre-Pubertal	149.3 ± 39.0	-	154.6 ± 17.7	230.8 ± 127.2
	Pubertal	256.4 ± 50.3 [a]	261.4 ± 60.6 [a]	334.6 ± 101.6 [a]	338.4 ± 134.3
	Post-Pubertal	389.4 ± 204.8 [a]	321.1 ± 86.8 [a]	381.5 ± 29.1 [a]	349.8 ± 105.3
Relative MP ($W·Kg^{-1}$)	Pre-Pubertal	4.3 ± 0.8	-	5.0 ± 0.7	5.4 ± 2.0
	Pubertal	4.5 ± 0.7	5.9 ± 1.4	6.6 ± 2.3	5.9 ± 2.5
	Post-Pubertal	6.1 ± 3.5	5.0 ± 1.0	5.9 ± 0.5	5.2 ± 1.2
Max Velocity ($m·s^{-1}$)	Pre-Pubertal	5.82 ± 0.41	-	6.23 ± 0.21	6.92 ± 1.33
	Pubertal	6.10 ± 0.37	6.55 ± 0.43	6.85 ± 0.74**	6.86 ± 1.01
	Post-Pubertal	6.54 ± 0.93	6.49 ± 0.50	6.84 ± 0.12**	6.63 ± 0.71
Average Velocity ($m·s^{-1}$)	Pre-Pubertal	5.24 ± 0.23	-	5.52 ± 0.21	5.73 ± 1.09
	Pubertal	5.18 ± 0.27	5.61 ± 0.28	5.67 ± 0.52	5.51 ± 0.64
	Post-Pubertal	5.45 ± 0.69	5.60 ± 0.33	5.61 ± 0.11	5.60 ± 0.30
30m Sprint Time (s)	Pre-Pubertal	5.73 ± 0.24	-	5.44 ± 0.21**	5.36 ± 0.99
	Pubertal	5.80 ± 0.29	5.36 ± 0.29	5.32 ± 0.48**	5.50 ± 0.59
	Post-Pubertal	5.56 ± 0.63	5.37 ± 0.31	5.36 ± 0.11**	5.37 ± 0.29
Fatigue Index (%)	Pre-Pubertal	92.2 ± 2.5	-	90.1 ± 0.8	82.7 ± 8.6
	Pubertal	88.6 ± 2.9	88.1 ± 4.6	86.9 ± 2.7	82.0 ± 6.5
	Post-Pubertal	88.5 ± 3.3	89.5 ± 2.5	85.3 ± 3.3	86.3 ± 11.3

All values presented as mean ± SD, $\dot{V}O_2$ = Oxygen Uptake, GET = Gas Exchange Threshold, PP = Peak Power, MP =

*Significant difference between baseline and post-intervention within groups ($p < 0.05$)

**Significant difference between control group and the HIIT groups ($p < 0.05$)

[a] Significant difference compared to pre-pubertal subjects at baseline and follow-up

[b] Significant difference compared to pubertal subjects at baseline and follow-up