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ORIGINAL ARTICLE

Critical power in adolescents: physiological bases and assessment using all-out exercise

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Abstract This study examined whether critical power (CP) in adolescents: (1) provides a landmark for maximal steady-state exercise; and (2) can be determined using 'all-out' exercise. Nine active 14–15 year olds (6 females, 3 males) performed five cycling tests: (1) a ramp test to determine $\dot{V}O_{2\,peak}$; (2) up to four constant power output tests to determine CP; (3–4) constant power output exercise 10% above and 10% below CP; and (5) a 3 min all-out cycle test to establish the end power (EP) at 90 and 180 s of exercise. All participants completed 30 min of exercise below CP and were characterized by steady-state blood lactate and $\dot{V}O_2$ profiles. In contrast, time to exhaustion during exercise above CP was 15.0 ± 7.0 min and characterized by an inexorable rise in blood lactate and a rise, stabilization (~91% $\dot{V}O_{2\,peak}$) and fall in $\dot{V}O_2$ (~82% $\dot{V}O_{2\,peak}$) prior to exhaustion. Eight out of nine participants completed the 3 min test and their EPs at 90 s (148 ± 29 W) and 180 s (146 ± 30 W) were not different from CP (146 ± 27 W) ($P = 0.98$). The typical error of estimates for establishing CP using EP at 90 s or 180 s of the 3 min test were 25 W (19.7% CV) and 25 W (19.6% CV), respectively. CP in active adolescence provides a valid landmark for maximal steady-state exercise, although its estimation on an individual level using the 3 min all-out test may be of limited value.

Keywords Fitness testing · Aerobic fitness · Exercise intensity domains · Maximal lactate steady-state

Introduction

The tolerable duration of high-intensity exercise follows a hyperbolic function of power output where critical power (CP) represents the asymptote of the power-duration curve and the curvature constant (W') is mathematically equivalent to a finite capacity of work that can be expended above CP before exhaustion (Hill 1993; Jones et al. 2010). Physiologically, CP has been proposed to represent the highest rate of oxidative metabolism that can be sustained without the continuous depletion of W' (Jones et al. 2010). Traditionally, W' is considered to reflect the finite energetic contributions from muscle phosphocreatine (PCr), muscle glycogen and stored O_2 during exercise above CP (Hill 1993; Monod and Scherrer 1965; Moritani et al. 1981). However, more recent evidence suggests W' may be related to the accumulation of fatigue-inducing metabolites (e.g. inorganic phosphate, H^+) during high-intensity exercise (Ferguson et al. 2010).

In a recent review, Jones et al. (2010) identified CP as a 'critical threshold' for intramuscular metabolic (e.g. PCr, pH) and systemic (e.g. $\dot{V}O_2$, blood lactate) homeostasis during high-intensity exercise. During exercise at or below CP but above the gas exchange threshold (GET), $\dot{V}O_2$, blood lactate, muscle PCr and pH attain a steady-state profile (Jones et al. 2008; Poole et al. 1988). In contrast, exercise above CP results in an inexorable and predictable rise in $\dot{V}O_2$ and blood lactate, and fall in muscle PCr and pH, with $\dot{V}O_2$ attaining its maximum and muscle PCr being

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almost depleted (Jones et al. 2008; Poole et al. 1988). Based on these physiological profiles, Whipp et al. (2005) consider CP to demarcate the heavy and very heavy exercise intensity domains and to occur at a power output that is equivalent to the maximal lactate steady-state (MLSS; although see Pringle and Jones 2002).

Compared to adults, research on CP in young people is limited and its physiological significance poorly documented. Consistent with CP [or critical velocity (CV)] representing an important parameter of aerobic function in youth are strong associations with $\dot{V}O_{2\,peak}$ (Berthoin et al. 2003; Leclair et al. 2010; Williams et al. 2008), sub-maximal blood lactate concentrations (Denadai et al. 2000) and endurance performance (Hill et al. 1995). However, based on the $\dot{V}O_2$ and blood lactate responses during cycling at CP, Williams et al. (2008) concluded that CP did not represent sustainable steady-state exercise in 12 to 13-year-old boys. In particular, these authors noted a non steady-state $\dot{V}O_2$, during exercise at CP and 10% above CP, and while $\dot{V}O_2$ projected towards $\dot{V}O_{2\,peak}$ in both conditions, only three out of ten adolescents attained their $\dot{V}O_{2\,peak}$, which surprisingly was also the case during the CP trial (Williams et al. 2008). These findings therefore challenge the notion that CP demarcates the heavy and very heavy exercise intensity domains in youth and warrant further investigation.

The traditional assessment of CP requires repeat constant power output trials to exhaustion to be performed over a single or on separate days which may account for the paucity of related studies in youth. A promising recent development in adults, is that the end power output (EP) and work performed above EP (WEP) during a single 3 min 'all-out' cycle test provides a valid measurement of CP and W', respectively (Vanhatalo et al. 2007). During all-out exercise above CP, W' will become expended and the resulting stabilization in power output would equal CP:

$$\text{Power} = CP + W'/\text{time}$$

Due to the sustained intense effort required during the 3 min test, $\dot{V}O_{2\,peak}$ is achieved (Burnley et al. 2006; Vanhatalo et al. 2007). As during 90 s all-out cycling young people attain a high (>90%) proportion of their $\dot{V}O_{2\,peak}$ and show signs of a stabilized power output (Carter et al. 2005; Williams et al. 2005), it may be feasible to determine CP using all-out exercise in young people, thus overcoming the requirement for multiple exhaustive exercise bouts using the traditional assessment method. However, Dekerle et al. (2009) have recently shown that the EP (140 ± 8 W) following 90 s of all-out isokinetic cycling exercise does not reflect CP (105 ± 6 W) in 12-year-old boys and girls. Whether an all-out test of longer duration would allow the identification of CP in this population is currently unknown.

The purpose of this study was to examine the physiological responses of adolescents to constant power output exercise above and below CP and to examine the utility of the 3 min all-out test to establish CP. It was hypothesized that: (1) CP in adolescents represents the boundary between heavy and very heavy exercise, and (2) that the EP during a 3 min all-out cycle test will provide a valid measurement of CP, as determined using repeated constant power output trials to exhaustion.

Methods

Participants

Nine 14 to 15-year-old adolescents (6 females, 3 males) volunteered to take part in the study. The participants' mean age, stature and body mass were 14.5 ± 0.3 years, 1.62 ± 0.08 m and 55.5 ± 4.5 kg, respectively. All participants and their parent(s)/guardian(s) provided informed assent and consent to partake in the project, which was approved by the institutional ethics committee. The participants were healthy, showed no contraindications to exercise to exhaustion, and were involved in competitive sports.

Experimental protocol

This study comprised of five parts whereby the participants completed a total of 7–8 exercise tests over 5 days within a 2 week period and with at least 24 h rest between each test (except for part 2, see below). All participants were requested to refrain from food and caffeine at least 2 h prior to testing. All tests were performed on a calibrated electronically braked cycle ergometer (Lode, Groningen, Netherlands).

Part 1: peak $\dot{V}O_2$ and GET determination. Following a 3 min period of cycling at 10 W, a ramp incremental test to exhaustion was undertaken whereby power output increased at a rate of 15–20 W min^{-1}. Participants cycled at a cadence of ~75 rpm throughout the test and exhaustion was defined as a drop in cadence below 60 rpm for 5 consecutive seconds. Peak power was recorded as the highest 15 s average. Pulmonary $\dot{V}O_2$ was monitored throughout the test and the highest recorded 15 s average was taken at the participants' $\dot{V}O_{2\,peak}$, which has recently been shown, through the use of supra-maximal exercise, to reflect a maximum $\dot{V}O_2$ in ~93% of young people performing ramp exercise (Barker et al. 2011). As supra-maximal exercise trials were not performed in the present study, the term $\dot{V}O_{2\,peak}$ will be used. The $\dot{V}O_2$ corresponding to the GET was established by identifying a disproportionate increase in expired carbon dioxide ($\dot{V}O_2$) relative to $\dot{V}O_2$ and using plots of the ventilatory equivalents for $\dot{V}O_2$ and $\dot{V}CO_2$ against time (Wasserman et al. 2005).

Part 2: determination of CP and W′. CP and W' were determined from three constant power output trials to exhaustion completed within a single day and with at least 3 h rest between each trial. This procedure has been shown to produce a valid estimate of CP in young people compared to performing three (mean bias = 1 ± 12 W) or five (mean bias = 2 ± 12 W) trials over separate days (Fawkner and Armstrong 2002). The initial trial was conducted at the power output that elicited $\dot{V}O_{2\,peak}$ during the ramp test and subsequent trials were modified on an individual basis using power outputs between ~70 and 95% $\dot{V}O_{2\,peak}$. This ensured the duration of the three trials ranged between 2 and 15 min and that the shortest and longest trial differed by more than 5 min (Bishop and Jenkins 1995; Hill 1993; Housh et al. 1990). If these criteria were not satisfied, a fourth predictive trial was conducted on a separate day following at least 24 h of rest. Before each predictive trial, the participants completed 6 min of baseline cycling at 10 W followed by a square-wave increase in power output to the target intensity. Participants were blinded to the exercise intensity and elapsed time, and were requested to cycle at a cadence of ~75 rpm until exhaustion. Throughout the tests participants received strong verbal encouragement. Time to exhaustion was recorded to the nearest second.

Following completion of the trials, regression analyses (GraphPad Prism, GraphPad Software, San Diego, CA, USA) were used to identify CP and W' using a linear time^{-1} model (power = CP + W'·time^{-1}), where CP and W' represent the Y-intercept and the slope, respectively (Hill 1993; Jones et al. 2008; Poole et al. 1988). This model was selected to facilitate inter-study comparisons with previous CP studies in young people (Fawkner and Armstrong 2002; Leclair et al. 2010; Williams et al. 2008). The goodness of fit of the regression model was determined by the adjusted coefficient of determination (R^2) and standard error of the estimate (SEE).

Parts 3 and 4: exercise above and below CP. On separate days and in a randomized order, participants completed constant power output trials at 10% above and 10% below CP. The participants received strong verbal encouragement during the tests, were blinded to the experimental trial and elapsed time, and were instructed to cycle for 30 min whilst maintaining a cadence of ~75 rpm. The test was terminated if the participant either completed 30 min of exercise, or became exhausted. Exercise duration was recorded to the nearest second. Throughout the tests, $\dot{V}O_2$ was measured using 15 s averages and heart rate recorded on a beat to beat basis and averaged over 5 s. Blood lactate was determined every 5 min during exercise and immediately post exhaustion if 30 min of exercise was not attained. A steady-state blood lactate profile was defined as an increase ≤1.0 mmol L^{-1} between 10 and 30 min of exercise (Beneke et al. 1996).

Part 5: three-min all-out cycle test. To part-familiarize the participants with the all-out effort required during the 3 min cycle test, three 10 s practice sprints were initially performed following a 5 min warm-up at ~80% GET. In these practice sprints, the participants were instructed to reach their highest cadence as quickly as possible against the resistance used on the 3 min test. Following 20 min of seated rest, each participant cycled at ~75 rpm for 6 min at a baseline of 10 W. In the final 5 s leading into the 3 min sprint each participant was instructed to raise their cadence to ~110 rpm and on the word "go", to attain their highest cadence as quickly as possible and to maintain a maximal effort for the entire test by keeping the cadence as high as possible at all time. The resistance for the test was calculated using the linear mode function (linear factor = power cadence^2), such that on attaining a cadence of 75 rpm, the power output would be equivalent to 50% of the difference (% Δ) between the $\dot{V}O_{2\,peak}$ and GET (Burnley et al. 2006; Vanhatalo et al. 2007). Power output was recorded every 1 s and averaged every 15 s for further analysis. Throughout the test, the participants received strong verbal encouragement and were blinded to the test duration to prevent pacing. The latter was identified visually by two researchers as systematic decreases and increases in power output over the test.

Experimental measures

Pulmonary gas exchange and ventilation were determined at 15 s averages using a commercially available system (Cortex Metalyzer II; Cortex Medical, Leipzig, Germany). Expired gasses were measured using an electrochemical cell (O_2) and infrared analyser (CO_2) following calibration against gases of known concentration. Flow was measured using a Triple®V digital sensor which was calibrated using a 3 L syringe (Hans Rudolph, Kansas City, USA) and securely fastened to the participant via a paediatric facemask (Hans Rudolph, Kansas City, USA). Heart rate was recorded using short-range radio telemetry (Polar Vantage NV, Polar Electro, Kempele, Finland). Whole blood lactate concentration was determined from a sample of ~5 µL of capillary blood collected from the participant's finger tip using a hand-held portable analyzer (Lactate Pro, Arkray, Japan) which was calibrated and verified prior to each sample using the manufacturer's calibration and test strips.

Statistical analyses

Analysis of the physiological variables or power output against time was achieved using either a 2- or 1-way repeated measures ANOVA. When appropriate, the Greenhouse-Geisser correction factor was applied to the ANOVA model degrees of freedom when Mauchly's test of sphericity was violated. Significant differences were followed-up using planned pair-wise comparisons employing the Bonferroni correction. The validity of using the 3 min all-out test to establish CP, W' and $\dot{V}O_{2\,peak}$ compared to the traditional measurement methods was achieved using mean bias, typical error of the estimate [absolute and expressed as a coefficient of variation (CV)], and Pearson's correlation coefficient (Hopkins 2000). Significance of the mean bias was examined using a paired sample t test. All statistical procedures were performed using SPSS (version 15.0, Chicago, USA), with the null hypothesis rejected at an alpha level of 0.05. Data are reported as mean ± SD.

Results

Peak $\dot{V}O_2$ and GET

The mean duration of the ramp test to exhaustion was 12 min 27 s ± 2 min 15 s, which resulted in a peak power output of 232 ± 27 W. Peak mean physiological variables during ramp exercise were: $\dot{V}O_2 = 2.67 \pm 0.52$ L min^{-1} (48.3 ± 10.7 mL kg^{-1} min^{-1}), RER = 1.14 ± 0.06, and heart rate = 199 ± 6 beats min^{-1}. The GET occurred at a $\dot{V}O_2$ of 1.35 ± 0.29 L min^{-1} which equated to 51 ± 7% peak $\dot{V}O_2$ and 107 ± 24 W.

CP and W' estimates

The power outputs employed during the shortest and longest trials to establish the participants' power-duration curve were 232 ± 27 and 170 ± 30 W with respective times to exhaustion of 2 min 28 s ± 0 min 25 s and 10 min 22 s ± 2 min 19 s. The peak heart rates over the four predictive trials were virtually indistinguishable ranging from 190 ± 7 beats min^{-1} (96 ± 4% $\dot{V}O_{2\,peak}$) to 191 ± 5 beats min^{-1} (97 ± 1% $\dot{V}O_{2\,peak}$). An example power-duration curve with CP and W' estimated using the linear time^{-1} model is shown in Fig. 1. When applying the linear model the CP and W' estimates were 149 ± 27 W and 12.5 ± 2.9 kJ, respectively (adjusted $R^2 = 0.98 \pm 0.03$ and SEE = 4 ± 3 W). Based on the linear relationship between $\dot{V}O_2$ and power output during the ramp test (9.81 ± 1.11 mL min^{-1} W^{-1}), the projected $\dot{V}O_2$ at CP was 1.79 ± 0.42 L min^{-1} (67 ± 6% $\dot{V}O_{2\,peak}$). The CP occurred at a lower and higher $\dot{V}O_2$ than $\dot{V}O_{2\,peak}$ ($P < 0.001$) and GET ($P = 0.003$) respectively, and equated to 31 ± 19% Δ.

Exercise 10% below and 10% above CP

Exercise 10% below and 10% above CP was performed at a mean power output of 134 ± 24 and 163 ± 30 W, respectively. This equated to ±15 W around CP which is equivalent to ~3.75-fold the SEE for CP. All participants successfully completed 30 min of exercise during the below CP trial. Above CP the mean time to exhaustion was 14 min 59 s ± 6 min 57 s with only a single participant managing to complete 30 min of exercise. Time to exhaustion in the above CP trial was not different from that predicted by the linear time^{-1} model (14 min 3 s ± 4 min 18 s, $P = 0.80$; $r = 0.71$, $P = 0.033$). Representative $\dot{V}O_2$, $\dot{V}_E$ heart rate and blood lactate responses to exercise below and above CP are illustrated in Fig. 2.

As during the above CP condition blood lactate data for all participants were only available at 5 min and end-exercise, means comparisons were restricted to these time points. Two-way ANOVA revealed a significant trial by time interaction for blood lactate ($P = 0.033$). Blood lactate was significantly elevated in the above compared to the below CP condition both at 5 min (7.4 ± 1.7 vs. 4.7 ± 0.5 mmol L^{-1}; $P = 0.001$) and at end-exercise (10.4 ± 3.0 vs. 4.7 ± 0.5 mmol L^{-1}; $P = 0.001$). During exercise below CP, blood lactate did not increase between 5 min and end-exercise (i.e. 30 min; $P = 0.90$), whereas a significant increase in blood lactate was observed between 5 min and end-exercise above CP ($P = 0.008$). During the below CP trial, seven of eight participants (one participant requested not to have their blood lactate measured in the

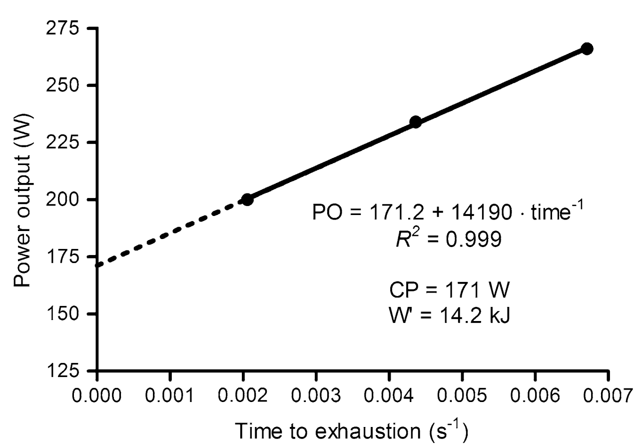

Fig. 1 Example power-duration curve of a representative participant who completed three constant power output trials to exhaustion. Estimation of CP and W' is achieved using the linear time^{-1} model

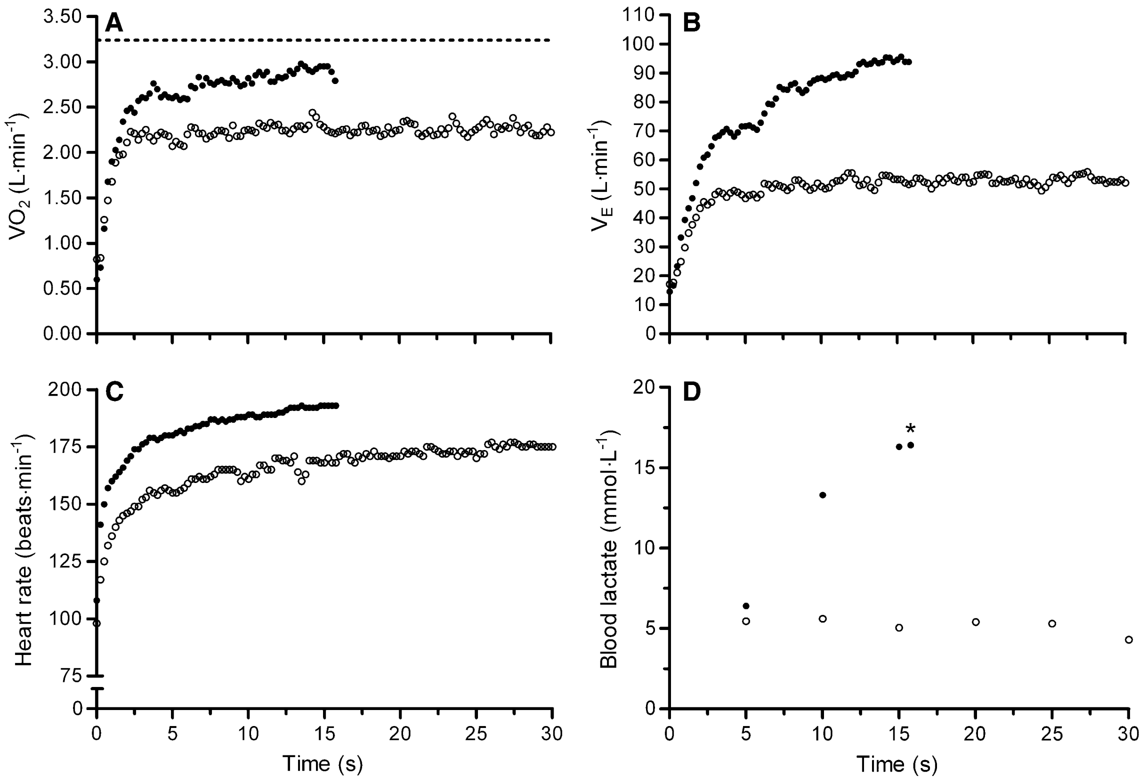

Fig. 2 Representative $\dot{V}O_2$ (**a**), $\dot{V}_E$ (**b**), heart rate (**c**) and blood lactate (**d**) responses during constant power output exercise 10% below (*open circle*) and 10% above (*filled circle*) CP. The *horizontal dotted line* in **a** denotes the $\dot{V}O_{2\,peak}$ achieved during the ramp cycle test. The *asterisk* in **d** denotes the blood lactate measurement immediately post exhaustion

below CP trial) met the criterion for a steady-state blood lactate profile. The mean change in blood lactate between 10 and 30 min was 0.0 ± 0.7 mmol L^{-1}.

As between-participant differences existed in time to exhaustion in the above CP trial, physiological responses are presented in relative percentage time to exhaustion (Table 1) and absolute time (Table 2). However, as the statistical outcomes were essentially similar for both expressions of time, the relative time output comparisons will be provided below. Repeated measures ANOVA revealed a significant trial by time interaction for $\dot{V}O_2$ ($P < 0.001$). Follow-up comparisons identified a higher $\dot{V}O_2$ during exercise above CP compared to below CP at 20 ($P = 0.049$), 40 ($P = 0.013$), 60 ($P < 0.001$) and 80% ($P = 0.002$) of end-exercise. At baseline ($P = 1.00$) and end-exercise (100%; $P = 0.09$), mean differences for $\dot{V}O_2$ were not observed between conditions. During exercise below CP, $\dot{V}O_2$ increased from baseline to 20% end-exercise ($P < 0.001$), but remained stable thereafter ($P > 0.45$). For exercise above CP, $\dot{V}O_2$ increased from baseline to 20% ($P < 0.001$), and 20–40% end-exercise ($P = 0.006$). Between 40 and 60% ($P = 0.07$) and 60 and 80% ($P = 0.67$) end-exercise, however, $\dot{V}O_2$ remained stable, before showing a fall between 80 and 100% ($P = 0.029$). At end-exercise in the below CP condition, $\dot{V}O_2$ attained $74 \pm 7\%$ of the ramp determined $\dot{V}O_{2\,peak}$. In contrast, the highest 15 s average $\dot{V}O_2$ attained during exercise above CP (2.43 ± 0.46 L min^{-1}) attained $91 \pm 4\%$ (range: 86–98%) of the ramp exercise determined $\dot{V}O_{2\,peak}$ ($P < 0.001$), and fell to $82 \pm 9\%$ (range: 70–94%) $\dot{V}O_{2\,peak}$ at exhaustion.

Repeated measures ANOVA found a significant trial by time interaction for $\dot{V}_E$ ($P < 0.001$). During the above CP $\dot{V}_E$ was elevated compared to below CP at 40 ($P = 0.007$), 60 ($P = 0.004$), 80 ($P = 0.005$) and 100% ($P = 0.008$) end-exercise. No significant trial differences in $\dot{V}_E$ were present at baseline ($P = 1.0$) or 20% ($P = 0.10$) end-exercise. During exercise below CP $\dot{V}_E$ rose from baseline to 20% end-exercise ($P < 0.001$) but remained stable thereafter ($P > 0.07$). However, in the above CP trial $\dot{V}_E$ rose across all time points up to 80% end-exercise ($P < 0.035$), with a trend for a fall at end-exercise ($P = 0.06$).

Repeated measures ANOVA revealed a significant trial by time interaction for heart rate ($P = 0.024$). Follow-up comparisons identified an elevated heart rate during exercise above compared to below CP at 40 ($P = 0.047$), 60 ($P = 0.006$), 80 ($P = 0.006$) and 100% ($P = 0.017$)

Table 1 Physiological responses during exercise below and above CP against relative time

Variable	Relative time (% end-exercise)					
	0	20	40	60	80	100
$\dot{V}O_2$ (L min^{-1})						
Below CP	0.72 ± 0.19	1.89 ± 0.30*,†	1.92 ± 0.34*	1.95 ± 0.37*	1.93 ± 0.31*	1.97 ± 0.29
Above CP	0.64 ± 0.11	2.10 ± 0.43†	2.25 ± 0.48†	2.29 ± 0.46	2.27 ± 0.44	2.19 ± 0.43†
$\dot{V}_E$ (L min^{-1})						
Below CP	16.3 ± 3.9	44.2 ± 5.9†	46.6 ± 7.1*	46.4 ± 7.8*	46.0 ± 5.2*	46.7 ± 6.9*
Above CP	15.0 ± 2.5	53.2 ± 12.8†	58.5 ± 13.6†	63.6 ± 15.4†	66.8 ± 15.9†	64.1 ± 15.4
Heart rate (beats min^{-1})						
Below CP	111 ± 17	164 ± 10†	172 ± 10*,†	173 ± 9*	174 ± 8*	177 ± 9*,†
Above CP	110 ± 17	170 ± 10†	180 ± 8†	185 ± 10†	188 ± 9†	189 ± 9†

Data are reported as mean ± SD. The specific *P* values are provided in the text

* A significant mean difference between conditions at a given time point

† A significant mean difference compared to the preceding time point within a condition

Table 2 Physiological responses during exercise below and above CP against absolute time

Variable	Absolute time (min)					
	0	1	2	4	8	End-exercise
$\dot{V}O_2$ (L min^{-1})						
Below CP	0.72 ± 0.19	1.47 ± 0.30*,†	1.78 ± 0.30*,†	1.87 ± 0.37*	1.88 ± 0.31*	1.97 ± 0.29†
Above CP	0.64 ± 0.11	1.65 ± 0.27†	2.00 ± 0.41†	2.23 ± 0.45†	2.26 ± 0.43	2.19 ± 0.41
$\dot{V}_E$ (L min^{-1})						
Below CP	16.3 ± 3.9	29.6 ± 6.4*,†	40.6 ± 7.3*,†	42.8 ± 7.2*	43.8 ± 5.4*	46.7 ± 6.9*,†
Above CP	15.0 ± 2.5	35.4 ± 7.1†	49.5 ± 10.9†	57.7 ± 13.2†	63.2 ± 13.5†	64.1 ± 15.4
Heart rate (beats min^{-1})						
Below CP	111 ± 17	145 ± 13†	153 ± 13*,†	161 ± 11*,†	167 ± 10*,†	177 ± 9*,†
Above CP	110 ± 17	153 ± 14†	165 ± 13†	176 ± 11†	184 ± 11†	189 ± 9†

Data are reported as mean ± SD. The specific *P* values are provided in the text

* A significant mean difference between conditions at a given time point

† A significant mean difference compared to the preceding time point within a condition

end-exercise. No differences in heart rate were present at baseline ($P = 1.0$) and 20% ($P = 0.29$) end-exercise. During exercise below CP, heart rate increased between 0 and 20% ($P < 0.001$) and 20 and 40% ($P = 0.001$), but remained stable until 80% ($P > 0.09$), where a further increase was observed between 80 and 100% end-exercise ($P = 0.048$). In contrast, exercise above CP resulted in an increase in heart rate across all time points ($P < 0.03$). The peak heart rate obtained during the above CP test was 190 ± 9 beats min^{-1} or 96 ± 3 % of the ramp determined peak heart rate ($P = 0.004$).

All-out cycle test

Out of the nine participants, the data from a single participant was not considered suitable for analysis due to signs of pacing. Of the remaining eight participants, their mean power output profile during the 3 min cycle test is illustrated in Fig. 3a. Peak power output and total work done during the 3 min cycling test was 492 ± 89 W and 36.8 ± 6.0 kJ, respectively. Peak power output occurred at 6 ± 3 s, which was equivalent to a peak cadence of 134 ± 7 rpm. At the end of the 3 min test cadence had fallen to 73 ± 5 rpm. ANOVA revealed a significant difference in power output over time during the 3 min cycle test ($P < 0.001$). Decrements in power output were identified from 15 to 75 s of exercise ($P < 0.001$) and a strong trend between 75 and 90 s ($P = 0.09$), after which no further fall in power output was observed up to 180 s of exercise ($P > 0.39$). The mean change in power output from 90 to 180 s was −1 ± 13 W, highlighting, at a group level, power output had attained a plateau after 90 s of exercise (Fig. 3b). Subsequent analyses of the 3 min cycle test data were undertaken using the 15 s data averages at 90 and 180 s of exercise.

The responses of $\dot{V}O_2$, $\dot{V}_E$ and heart rate during the 3 min test are illustrated in Fig. 4. A significant difference for $\dot{V}O_2$, $\dot{V}_E$ and heart rate (all $P < 0.001$) over time was found for the 3 min test. A significant increase in $\dot{V}O_2$ was identified from 15 to 45 s ($P < 0.003$) after which $\dot{V}O_2$ stabilized ($P > 0.053$) and fell between 90 and 105 s ($P = 0.019$) and 165–180 s ($P = 0.040$). Likewise, $\dot{V}_E$ increased from 15 to 45 s ($P < 0.005$) but stabilized thereafter ($P > 0.143$) and fell between 135 and 150 s ($P = 0.027$) and 165 and 180 s ($P = 0.008$). Finally, heart rate increased from 15 to 45 s ($P < 0.004$) but remained stable thereafter ($P > 0.06$). However, the peak heart rate obtained during the 3 min test (190 ± 7 beats min^{-1}) was significantly higher than that measured at 180 s (183 ± 10 beats min^{-1}; $P = 0.037$).

The EP, WEP and $\dot{V}O_{2\,peak}$ from the 3 min all-out cycle test compared to traditional measurement procedures are provided in Table 3. No significant differences were observed for $\dot{V}O_{2\,peak}$ at 90 and 180 s of the all-out cycle test compared to the ramp test ($P = 0.35$; Fig. 4a). On average $\dot{V}O_{2\,peak}$ occurred 86 ± 41 s into the 3 min test, after which $\dot{V}O_2$ declined to 2.28 ± 0.47 L min^{-1} at end-exercise

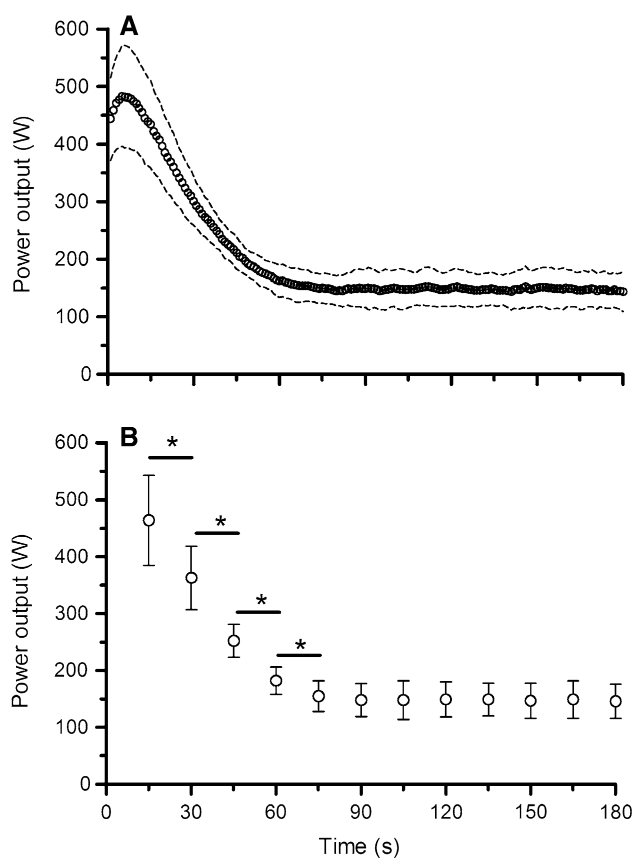

Fig. 3 Mean power output profile during the 3 min all-out cycle test using 1 s (**a**) and 15 s (**b**) averages. *Asterisk* denotes significant mean differences between subsequent 15 s data bins

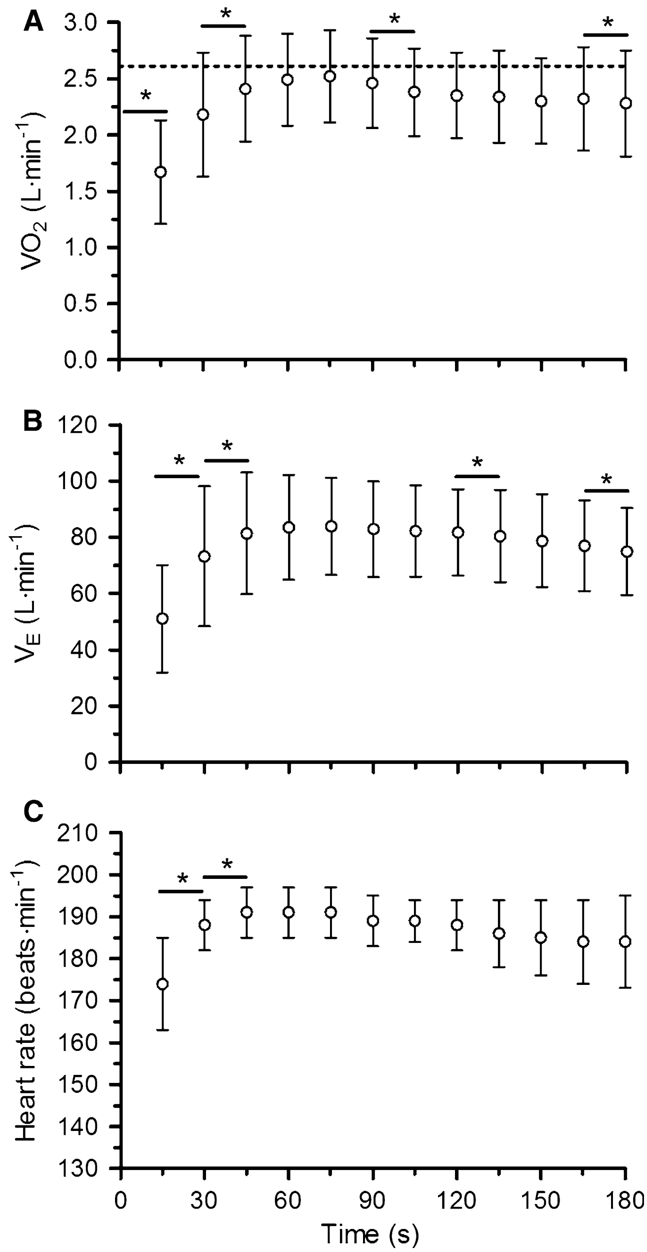

Fig. 4 Mean $\dot{V}O_2$ (**a**), $\dot{V}_E$ (**b**) and heart rate (**c**) responses during the 3 min all-out cycle test. The *horizontal line* in **a** represents the mean $\dot{V}O_{2\,peak}$. All data are presented as 15 s averages. *Asterisk* denotes significant mean differences between subsequent 15 s data bins

which was significantly lower than the ramp determined $\dot{V}O_{2\,peak}$ ($P = 0.022$, ~87% $\dot{V}O_{2\,peak}$) but not end-exercise $\dot{V}O_2$ during the 10% above CP trial ($P = 0.31$). The magnitude of the fall in $\dot{V}O_2$ from $\dot{V}O_{2\,peak}$ to end-exercise during the 3 min test was comparable to that observed in the above CP trial (0.28 ± 0.27 vs. 0.24 ± 0.18; $P = 0.74$), but was not related ($r = 0.09$, $P = 0.83$). No significant differences were observed for CP/EP ($P = 0.98$) and W'/WEP ($P = 0.19$) using data at 90 and 180 s of the all-out cycle test.

End power at 90 and 180 s of the 3 min test was significantly lower than peak power output achieved during the ramp test ($P < 0.001$) and higher than the power output at the GET ($P < 0.001$). On average, EP at 90 and 180 s of the 3 min test occurred at 34 ± 16 and 33 ± 18% Δ, respectively. The validity statistics between $\dot{V}O_{2\,peak}$, EP and WEP calculated using 90 and 180 s of data from the 3 min test against traditional assessment methods are shown in Table 4.

Discussion

In accordance with our first hypothesis, constant power output exercise performed 10% below and 10% above CP resulted in a physiological profile that is consistent with CP demarcating the heavy and very heavy intensity domains. Exercise below CP was characterized with a steady-state $\dot{V}O_2$ and blood lactate profile. In contrast, time to exhaustion was markedly reduced during exercise above CP and blood lactate increased inexorably with time. However, while $\dot{V}O_2$ initially rose continuously with time during the above CP trial, its zenith stabilized close to, but below $\dot{V}O_{2\,peak}$, and later fell prior to exhaustion. In agreement with our second hypothesis, EP during the 3 min all-out test was not significantly different from CP determined using repeated constant power output trials. As power output during the 3 min test had stabilized after ~90 s, we also found no difference between EP at 90 s and CP. However, the magnitude of the typical error of estimate for EP restricts the utility of using either a 90 s or 3 min all-out tests to estimate CP on an individual level.

CP and W' estimates

It is well established that in adult humans the tolerable duration of high-intensity exercise follows a hyperbolic

Table 3 Comparison of the 3 min all-out cycle test against traditional measurement procedures

	Ramp			Linear time^{-1} model		90 s cycle test			180 s cycle test		
	$\dot{V}O_{2\,peak}$ (L min^{-1})	Peak power (W)	Power at GET (W)	CP (W)	W' (kJ)	EP (W)	WEP (kJ)	$\dot{V}O_{2\,peak}$ (L min^{-1})	EP (W)	WEP (kJ)	$\dot{V}O_{2\,peak}$ (L min^{-1})
1	2.99	243	85	180	8.5	130	11.1	2.93	120	12.5	2.93
3	2.61	210	123	120	16.6	144	8.2	2.30	146	8.3	2.30
4	2.36	240	137	152	14.9	152	10.5	2.43	141	11.8	2.43
5	1.88	188	83	104	10.1	131	6.7	1.82	115	8.5	1.92
6	1.91	198	73	121	10.5	103	11.6	2.14	112	10.9	2.14
7	3.24	266	106	171	14.2	196	12.3	2.96	181	14.5	2.96
8	3.07	243	117	160	11.5	150	10.3	2.87	164	9.6	2.98
9	2.78	243	97	160	10.4	176	10.0	2.79	192	9.1	2.79
Mean	2.61	229*	103*	146	12.1	148	10.1	2.53	146	10.6	2.56
SD	0.52	27	22	27	2.8	29	1.8	0.42	30	2.2	0.41

* Significant difference from the EP determined at 90 and 180 s of the 3 min test. The specific P values are provided in the text

Table 4 Validity analyses for peak $\dot{V}O_2$, EP and WEP calculated from the 90 and 180 s tests against traditional assessment methods

	Mean bias	Typical error of estimate	95% confidence intervals	Pearson's correlation
Peak $\dot{V}O_2$ (L min^{-1})				
Ramp versus $\dot{V}O_{2\,90s}$	−0.07	0.18 (8.1%)	0.12–0.41	0.95†
Ramp versus $\dot{V}O_{2\,180s}$	−0.05	0.18 (7.6%)	0.11–0.39	0.95†
CP (W)				
Linear versus EP_{90s}	2	25 (19.7%)	16–55	0.54
Linear versus EP_{180s}	0	25 (19.6%)	16–56	0.52
W' (kJ)				
Linear versus WEP_{90s}	−2.0	3.0 (28.0%)	2.0–6.7	0.05
Linear versus WEP_{180s}	−1.4	3.0 (28.0%)	2.0–6.7	0.03

The typical error of estimate is expressed in their measurement units and as a coefficient of variation in parentheses

* A significant Pearson's correlation ($P < 0.05$)

† A significant Pearson's correlation ($P < 0.01$)

function of power output (Hill 1993; Jones et al. 2010). Although more complex 3-parameter models are available, the 2-parameter model provides a practical and physiologically sound characterization of performance during high-intensity exercise (Hill 1993; Jones et al. 2010). The robustness of the CP and W' estimates in the current study using the linear time^{-1} model appear acceptable given the high adjusted R^2 (0.98 ± 0.03) and low SEE (4 ± 3 W), which are comparable to previous studies on children and adults (Fawkner and Armstrong 2002; Poole et al. 1988; Pringle and Jones 2002; Williams et al. 2008).

The absolute CP estimate in the present study is higher than previous research on children aged 9–12 years (~90–125 W; Dekerle et al. 2009; Fawkner and Armstrong 2002; Leclair et al. 2010; Williams et al. 2008). Collectively though, the studies show CP to occur above and below the GET and $\dot{V}O_{2\,peak}$, respectively (~68–78% $\dot{V}O_{2\,peak}$), or ~30–50% Δ. These values are consistent with CP estimates reported in healthy adults during cycling exercise (Ferguson et al. 2010; Poole et al. 1988; Pringle and Jones 2002; Vanhatalo et al. 2007). To our knowledge, only the studies by Dekerle et al. (2009) and Leclair et al. (2010) have reported W' estimates in young people during cycling exercise. Both studies reported a W' of ~6–7 kJ in 9–12 year olds which represents ~50% of the W' reported in the current study. This difference remains, albeit smaller, when normalized for body mass (~170 vs. 224 J kg^{-1}). As W' in healthy young adults during cycling exercise is typically between 15.0 and 20.0 kJ (Ferguson et al. 2010; Pringle and Jones 2002; Vanhatalo et al. 2007), this suggests that W' increases during growth and maturation. Indeed, Leclair et al. (2010) reported an age-related increase in W' between prepubertal boys and men and attributed this finding to children's inferior ability to supply ATP via anaerobic metabolism during high-intensity exercise (e.g. Barker et al. 2010b).

Exercise above and below CP

This is the first study to systematically address the physiological responses of young people to exercise above and below CP. All participants completed 30 min of exercise 10% below CP and a steady-state blood lactate profile was identified in seven out of eight participants using the criterion of ≤1.0 mmol L^{-1} change between 10 and 30 min of exercise (Beneke et al. 1996). The steady-state blood lactate occurred at ~4.5 mmol L^{-1}, which corroborates well with estimates of MLSS determined using a series of constant power output trials in adolescents (Beneke et al. 1996). As expected, $\dot{V}O_2$ rose continuously during the initial ~8 min of exercise below CP due to the development of the $\dot{V}O_2$ slow component. Between 12 and 30 min, however, the mean increase in $\dot{V}O_2$ was ~0.04 L min^{-1}, indicating the attainment of a steady-state $\dot{V}O_2$ below maximum (~74% $\dot{V}O_{2\,peak}$). Exercise 10% above CP however, was strikingly different to the below CP condition. For an increase in ~28 W (~15 W above CP) the time to exhaustion was reduced to ~15 min with only a single participant managing to complete 30 min of exercise. Blood lactate rose inexorably with time and peaked at ~10 mmol L^{-1} at exhaustion. Moreover, during the above CP trial, $\dot{V}O_2$ rose progressively towards $\dot{V}O_{2\,peak}$ but stabilized at ~91% $\dot{V}O_{2\,peak}$ between 40 and 80% end-exercise, suggesting the attainment of a delayed sub-maximal steady-state $\dot{V}O_2$.

While collectively these data are consistent with the notion that the CP concept represents a 'critical threshold' for homeostasis during exercise in adolescents, as has previously been demonstrated in adults (reviewed in Jones et al. 2010), the $\dot{V}O_2$ profile during exercise above CP displayed unique characteristics that are worthy of further discussion. In adults, exhaustion during constant power output exercise above CP occurs with the attainment of $\dot{V}O_{2\,peak}$ (Hill et al. 2002; Özyener et al. 2001; Poole et al. 1988). However, between 80 and 100% end-exercise during the above CP trial, rather than attaining $\dot{V}O_{2\,peak}$, $\dot{V}O_2$ fell to ~82% $\dot{V}O_{2\,peak}$ at exhaustion. The unexpected fall in $\dot{V}O_2$ during exercise above CP may be further evidence for a so-called 'fourth phase' in $\dot{V}O_2$ kinetics. Perrey et al. (2002) found a reduction in $\dot{V}O_2$ prior to exhaustion in 7 out of 13 trained male participants whilst running at ~95% $\dot{V}O_{2\,peak}$. They also observed a concomitant reduction in $\dot{V}_E$ in six of the seven participants and suggested a respiratory limitation may be important. Further scrutiny of the fall in $\dot{V}O_2$ in the current study revealed this phenomenon was only manifest in four (2 males, 2 females) out of the nine adolescent participants and appeared not to be linked to $\dot{V}_E$ dynamics. While the present study is unable to provide insight into the mechanistic bases of a so-called 'fourth phase' in $\dot{V}O_2$ kinetics, it is interesting to note that heart rate (and presumably cardiac output; Barker et al. 2010a) continued to rise and attained ~95% peak during the above CP trial. According to the Fick principle, it is possible that factors relating to the ability of the muscle to extract and utilize O_2 (e.g. microcirculatory O_2 availability, rate of oxidative phosphorylation) may underlie the reduction in $\dot{V}O_2$ prior to exhaustion in the current study. However, as this phenomenon only occurs in ~40–55% of individuals exercising within the very heavy domain (present study; Perrey et al. 2002) further evaluation of its physiological and practical significance is required.

The data in the present study corroborate the findings of Poole et al. (1988) that CP occurs at a power output that is equivalent to MLSS. However, it should be noted that others have found CP to occur close to, but at a power output that is higher than MLSS (Dekerle et al. 2003; Pringle and Jones 2002). Furthermore, non-steady-state $\dot{V}O_2$ and blood lactate profiles whilst exercising at CP have been reported in adults (Brickley et al. 2002; Dekerle et al. 2010). In the only study to examine physiological responses during exercise at CP in youth, Williams et al. (2008) observed a continued rise in $\dot{V}O_2$ (reaching ~94% $\dot{V}O_{2\,peak}$ at exhaustion) and concluded that CP does not represent sustainable steady-state exercise in adolescent boys. Although it is currently unclear why CP is close to, but possibly above MLSS, it is pertinent to note that when exercise is performed just below or above CP (e.g. ±5–10%), the derived physiological profiles are consistent with CP representing a critical threshold for metabolic (e.g. PCr, pH) and systemic (e.g. $\dot{V}O_2$, blood lactate) homeostasis (Burnley et al. 2006; Dekerle et al. 2010; Jones et al. 2008, present study). It is possible that such inter-study discrepancies in the physiological response whilst exercising at CP are, in part, caused by methodological issues. The length of the CP predictive trials, inter-trial recovery, and choice of analysis model, all have the potential to significantly impact the CP estimate (Bishop and Jenkins 1995; Gaesser et al. 1995; Hill 1993; Housh et al. 1990). Given these considerations, the use of exercise slightly above or below CP may be a more useful approach to reveal the physiological significance of CP and its position within the intensity domain spectrum.

3 min all-out test

The assessment of CP typically requires multiple trials of fatiguing constant power output exercise to be performed over separate days or within the same day, which may explain its limited use in research and applied settings. However, a recent study has successfully applied all-out exercise to the CP concept, and found that the EP during a 3 min all-out cycle test provides a valid measurement of CP in healthy adults (Vanhatalo et al. 2007). Subsequently, Dekerle et al. (2009) examined whether the EP during a 90 s all-out isokinetic cycle test would equal CP in children. While a significant correlation between EP and CP was observed, EP represented ~135% of the latter, suggesting a test greater than 90 s in duration may be required to fully deplete W'.

In agreement with the original description (Burnley et al. 2006; Vanhatalo et al. 2007), we identified a stable power output profile during the 3 min test, which is consistent with W' being fully expended. In the current study, however, power output stabilized after ~90 s of exercise rather than the ~140 s reported in the original investigation (Burnley et al. 2006). This suggests that an all-out cycle test for ~90 s in duration may be suitable to determine CP (and W') in adolescents. However, while the EP both at 90 and 180 s of exercise were not significantly different from CP, the typical error of estimate (~25 W) is likely to be beyond acceptable limits given the profound physiological differences noted in the current study when constant power output exercise was performed 10% above and below CP. In particular, the results of the current study suggest either a 90 s or 3 min all-out test could result in an adolescent exercising ±17% around their actual CP.

The corresponding typical error of estimate for CP in adults using the 3 min test is 9 W or 3% CV, supporting the robust and precise measurement of CP using all-out exercise (Vanhatalo et al. 2007). This finding is in direct conflict to the adolescent data presented herein and warrants discussion. First, in the Vanhatalo et al. (2007) paper participants were fully familiarized to the 3 min test, whereas in the current study three 8–10 s practice sprints were used. Our rationale for using practice sprints was based on their use in previous studies examining the physiological responses of young people during a 90 s all-out cycling test (Dekerle et al. 2009; Williams et al. 2005), where the reliability of EP has a standard error of measurement of 12 W (Williams et al. 2008). As we were unable to detect a change in power output between 90 and 180 s of exercise during the 3 min test and found a close agreement between the 90 and 180 s EP data (Table 3), it is reasonable to assume a comparable reproducibility for EP in the current study. Second, Vanhatalo et al. (2007) used the participants' preferred cadence to set the resistance during the all-out test, whereas in the current study this was assumed to be 75 rpm for all individuals. As a ~10 rpm increase from an individual's preferred cadence may impact EP during the 3 min test by ~10 W (Vanhatalo et al. 2008), the adoption of a fixed cadence of 75 rpm in the current study may have influenced the agreement between EP and CP.

In agreement with the original studies of the 3 min test (Burnley et al. 2006; Vanhatalo et al. 2007), the adolescents in the current study achieved ~98 and ~100% of their ramp determined $\dot{V}O_{2\,peak}$ at 90 and 180 s of the 3 min test respectively, with the typical error of the estimate being ~0.18 L min^{-1} (~8% CV). These data are comparable with the study by Vanhatalo et al. (2007) (~0.17 L min^{-1} or 4% CV), and suggest a valid measurement of $\dot{V}O_{2\,peak}$ can be obtained in adolescents using either a 90 s or 3 min test. This outcome corroborates previous studies showing young people can achieve (Williams et al. 2005) or even exceed (Dekerle et al. 2009) their ramp determined $\dot{V}O_{2\,peak}$ during 90 s of all-out exercise.

An observation worthy of further comment in the current study is that while $\dot{V}O_{2\,peak}$ may be achieved in young people during all-out exercise where power output is falling and later stabilizes, a $\dot{V}O_{2\,peak}$ is rarely attained during constant power output exercise to exhaustion just above CP. However, while the adolescents in the present study attained $\dot{V}O_{2\,peak}$ during all-out exercise, unlike adults (Burnley et al. 2006; Vanhatalo et al. 2007), they were unable to sustain this for the remainder of the test; at the end of the 3 min test $\dot{V}O_2$ had fallen to ~87% $\dot{V}O_{2\,peak}$. Such a fall in $\dot{V}O_2$ is not evident during 90 s all-out exercise in young people (Fig. 1 in Carter et al. 2005), suggesting this phenomenon may be restricted to all-out exercise above 90 s in duration (see Fig. 4a). While explanation of this observation is not readily available in the current study, the fall in $\dot{V}O_2$ occurred whilst power output remained stable (i.e. O_2 cost of exercise was reduced). As a similar $\dot{V}O_2$ response was observed in the current study during constant power output exercise above CP, the two may be linked. However, while the end-exercise $\dot{V}O_2$ was not significantly different from the $\dot{V}O_2$ recorded at end-exercise during the above CP trial and the magnitude of the fall was comparable, the resulting correlation was weak ($r = 0.09$). Furthermore, during constant power output exercise above CP both $\dot{V}_E$ and heart rate continued to rise, but declined, following the attainment of their peak values, during the 3 min test. Further resolution of the unique $\dot{V}O_2$ responses in the current study is therefore required.

Conclusions

This is the first study to address the physiological responses during exercise above and below CP, and whether CP can be determined using a single all-out exercise test, in young people. As predicted by knowledge of the CP concept, exercise performed 10% above and below CP in adolescents corresponds to that expected for the heavy and very heavy intensity domains. That is, CP represents a critical threshold for power outputs which result in steady-state $\dot{V}O_2$ and blood lactate responses (heavy exercise) and those where $\dot{V}O_2$ and blood lactate rise with time until exhaustion (very heavy exercise). In contrast to adults however, a unique finding of the current study is that adolescents fail to attain $\dot{V}O_{2\,peak}$ and in some instances may even experience a fall in $\dot{V}O_2$ at exhaustion during very heavy exercise. The performance of a 3 min all-out cycling test resulted in a stable power output profile after ~90 s of exercise suggesting a single all-out cycle test may be a useful and time friendly alternative to determine CP in young people. However, despite having a small mean bias, the typical error of estimate for CP approached 25 W, which may result in an adolescent exercising in the order of ~17% above or below their actual CP. Further research is therefore required before all-out exercise can be used to provide a robust estimation of CP in youth.

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Conflict of interest None.

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