

# Physiological and performance characteristics of road, mountain bike and BMX cyclists

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## Abstract

The purpose of this research was to quantify several physiological and power output characteristics of high-performance road, cross-country mountain bike (XCMB), downhill mountain bike (DHMB) and bicycle motocross (BMX) cyclists. Twenty-four high-performance cyclists ( $27 \pm 7$  years;  $182 \pm 6$  cm;  $79.3 \pm 9.7$  kg;  $\sum 7SF 69 \pm 27$  mm;  $VO_2 \text{ MAX } 61.4 \pm 9.9 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) completed both an incremental ramp test and a power profile assessment (PPA) across two separate testing sessions. The PPA consisted of maximal efforts lasting 5 s, 15 s, 30 s, 60 s, 240 s, and 600 s. The ramp test provided measures of  $VO_2 \text{ MAX}$ , maximal aerobic power (MAP) and individual  $VO_2$ -power regression equations, whilst the PPA determined metabolic costs, anaerobic capacity and power output across each effort. The data demonstrated that road and XCMB cyclists possessed significantly ( $p < 0.05$ ) higher  $VO_2 \text{ MAX}$  ( $65.3$ - $69.6$  vs.  $52.4$ - $55.3 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) and anaerobic capacities ( $1.7$ - $1.8$  vs.  $0.9$ - $1.3$  L) than the DHMB and BMX cyclists. Further, the same cohorts produced significantly ( $p < 0.05$ ) greater MAP ( $5.8$ - $6.3$  vs.  $4.4$ - $4.7 \text{ W}\cdot\text{kg}^{-1}$ ), as well as relative mean power output across efforts lasting  $\geq 15$  s. The BMX and DHMB cyclists demonstrated greater peak power outputs ( $\sim 200$  W) across the shorter efforts of the power profile. The data demonstrate that the road and XCMB cyclists possessed higher aerobic physiological capacities and power outputs than the DHMB and BMX cyclists. The latter disciplines possessed greater explosive power outputs. Together, these findings reflect the specificity of selected traits that are possessed within each cycling discipline.

**Keywords:** cycling, power profile, mountain bike, BMX

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## Introduction

Within cycling, the measurement of physiological characteristics such as maximal aerobic ( $\dot{V}O_{2\text{MAX}}$ ) and anaerobic (Maximal Accumulated Oxygen Deficit [MAOD]) capacities has been used to quantify the efficiency of energy metabolism pathways (Impellizzeri et al., 2005a; Lucia, Hoyos and Chicharro, 2001). Secondly, power output measures recorded within laboratories and field settings allow a cyclist's physical work capacities to be quantified. Taken together, the integration of these measures provides blended data that relate to performance, training adaptation and talent identification potential across various cycling disciplines. To date, the majority of this research has focused on these capacities in road cycling athletes (Lee et al., 2002; Lucia et al., 1998; Lucia et al., 2001). However, the evolution of off-road cycling disciplines such as cross-country mountain

biking (XCMB), downhill mountain biking (DHMB) and bicycle motocross (BMX) has presented new opportunities for researchers to investigate such measures.

Past research has demonstrated that road and XCMB cyclists work at high intensities (80–90%  $HR_{\text{MAX}}$ ) for extended periods of time ( $>1$  hr) (Gregory, Johns and Walls, 2007; Padilla et al., 2000; Stapelfeldt, Schwirtz, Schumacher & Hillebrecht, 2004), which relies heavily on the oxidative supply of ATP. As such, a large amount of research has reported on measures of  $\dot{V}O_{2\text{MAX}}$  and maximal aerobic power (MAP) of these cyclists (Impellizzeri et al., 2005a; Impellizzeri et al., 2005b; Lee et al., 2002; Lucia et al., 2001; Padilla et al., 2000). Comparatively, little research has reported on such measures in DHMB and BMX cyclists. Due to the repeated sprint nature of DHMB and BMX cycling (Cowell, Cronin and McGuigan, 2011; Hurst and Atkins, 2006) it is likely that a high  $\dot{V}O_{2\text{MAX}}$  may facilitate greater PCr resynthesis during periods of low-intensity activity. This may allow higher power outputs when the track or race conditions require such efforts. However, due to the limited data currently reporting on the latter cycling formats, as to what extent the aerobic energy pathways influence performance remains unknown.

Currently, far less is known on the anaerobic characteristics of cyclists that may limit the potential for supramaximal ( $>\dot{V}O_{2\text{MAX}}$ ) power outputs reliant on



anaerobic metabolism (Craig et al, 1993; Jeukendrup, Craig and Hawley, 2000). Specifically, it has been suggested that anaerobic glycolysis contributes between 40–45% and 14–24% of ATP yield during all-out efforts lasting 1 min and 4 min, respectively (Jeukendrup et al., 2000), however, sparse data exists for cyclists outside of road or track competition. Anaerobic capacity is likely to be important in response to sprint situations within XCMB races, however, again this characteristic is rarely reported on (Impellizzeri and Marcora, 2007). Perhaps more intriguing is the little data reported for the relationship between anaerobic power and performance for cyclists in events that require short (3-10 s) explosive sprints, such as DHMB or BMX (Cowell et al., 2011; Herman et al., 2009; Hurst and Atkins, 2006).

Given the importance of both aerobic and anaerobic capacities, power profile assessments (PPA) have evolved to offer a highly useful performance test that quantifies race-specific power outputs across repeated efforts within a single laboratory testing session. The protocol incorporates maximal-intensity efforts ranging between 5 s to 10 min, offering training and competition specific power output data (Quod et al., 2009; Quod et al., 2010). The use of PPA may provide an efficient initial testing protocol for a range of cycling disciplines for training monitoring and talent identification. Therefore, the purpose of this research was to quantify the physiological and power output characteristics of high-performance road, XCMB, DHMB and BMX cyclists using a standardised PPA.

### Materials and methods

Twenty-four high-performance male cyclists (age  $27 \pm 7$  yr; height  $182 \pm 6$  cm; body mass  $79.3 \pm 9.7$  kg;  $\sum 7$  skinfolds  $69 \pm 27$  mm;  $\dot{V}O_{2\text{MAX}}$   $61.4 \pm 9.9$  mL·kg<sup>-1</sup>·min<sup>-1</sup>) volunteered to participate in the current study. This population was divided into separate sub-samples of road, XCMB, DHMB and BMX cyclists (see Table 1). All participants were competitive at state or national level competition during the previous 12 months. Prior to inclusion, all participants were screened for pre-existing health conditions and provided their informed consent following an explanation of testing procedures. The study was approved by the Human Research Ethics Committee of the University of Newcastle.

Each participant made two separate visits to the exercise-testing laboratory, separated by between 4–6 days. Participants were instructed to avoid strenuous exercise for 48 hr prior to each testing session and to avoid caffeine, alcohol or performance improving substances for 6 hours before each session. The initial testing session included a standardised progressive incremental exercise test, which was followed by a separate visit where cyclists completed their PPA. All testing was completed on each participant's own personal bicycle that was attached to a LeMond Revolution cycle ergometer (LeMond Fitness Inc., Woodinville, Washington, USA). The LeMond Revolution takes the place of the rear wheel, using the bicycle's normal drivetrain to adjust resistance, which

allows the use of equipment and bicycle geometry that is specific to each individual.

### Progressive Incremental Exercise Test

Participants completed an incremental cycling test to determine their  $\dot{V}O_{2\text{MAX}}$ . Each individual's  $\dot{V}O_2$ -power regression equation was also established to allow estimation of MAOD. The incremental cyclist test required participants to begin cycling at 100 W for the first 60 s, after which power output increased by 30 W·min<sup>-1</sup> until the test was stopped. This occurred when a participant could no longer maintain a cadence above 80 RPM or demonstrated at least two of the five criteria for  $\dot{V}O_{2\text{MAX}}$  (Bentley et al., 2001).

### Power Profile Assessment

In the second visit, participants completed a PPA to determine maximal peak power and mean power outputs across efforts of varying durations (Quod et al., 2009; Quod et al., 2010).

The PPA consisted of a single maximal effort of the following (in order):

- 5 s effort from a standing stationary position using a low gear to determine acceleration characteristics;
- 5 s effort from a standing rolling position using a higher gear to determine maximal power output;
- 15 s effort from a standing rolling position using a self-selected gear;
- 30 s effort from a standing rolling position using a self-selected gear;
- 60 s effort from a standing rolling position using a self-selected gear;
- 240 s effort from a standing rolling position using a self-selected gear;
- 600 s effort from a standing rolling position using a self-selected gear.

All efforts required maximal intensity by the participant and consistent verbal encouragement was provided throughout. Mean and peak power output and cadence were recorded for each effort within post-test analysis.

### Physiological and Performance Measures

During the incremental exercise test and the 60 s, 240 s and 600 s PPA efforts, expired gases were analysed using a Jaeger Oxycon Pro (CareFusion, Leibnizstrasse, Germany). The system was calibrated with known volumes and concentrations of gas (O<sub>2</sub>, CO<sub>2</sub>) prior to each test. Cycling specific data (power output, cadence, heart rate) was recorded at a frequency of 1 Hz using a LeMond Power Pilot (LeMond Fitness Inc., Woodinville, Washington, USA). Post-test, data was downloaded to a personal computer and analysed in Microsoft Excel (Microsoft Corporation™, Redmond, Washington, USA).

### Aerobic Capacity and Maximal Aerobic Power

Maximal aerobic capacity ( $\dot{V}O_{2MAX}$ ; mL·kg<sup>-1</sup>·min<sup>-1</sup>) was recorded for each cyclist as the highest 30 s average  $\dot{V}O_2$  during the incremental exercise test. Maximal aerobic power (MAP; W and W·kg<sup>-1</sup>) was determined for each cyclist from the incremental exercise test via the following equation adapted from Kuipers et al. (1985).

$$MAP = P_p + \{t_f \times [(V_f - P_p)/60]\}$$

where  $P_p$  is the power output (W) of the previous complete stage,  $V_f$  is the power output (W) at the final stage, and  $t_f$  is the time (s) at final power.

### Anaerobic Capacity and Peak Power

The Maximal Accumulated Oxygen Deficit (MAOD) was calculated for both the 60 s and 240 s efforts using the individual  $\dot{V}O_2$ -power relationships established during the first testing session, as per Medbo and Tabata (1988). These efforts most closely represented effective MAOD assessments of sprint and endurance cyclists based on the findings of Craig et al. (1995). Peak power output (W and W·kg<sup>-1</sup>) was assessed as the highest power value recorded throughout the PPA.

### Statistical analysis

Data is presented below as mean ± SD. Normality of data was assessed via Shapiro-Wilk tests as well as visually using Q-Q plots. Mean values for all measures were analysed between disciplines via one-way analysis of variance with Scheffe's post-hoc analysis. Pearson's product-moment correlations were also conducted to determine if any significant relationships existed between variables. Correlations were identified as 0.0-0.1 (trivial), 0.1-0.3 (small), 0.3-0.5 (moderate), 0.5-0.7 (large), 0.7-0.9 (very large), and 0.9-1.0 (near perfect) (Hopkins, 2002). The level of statistical significance for all measures was set at  $p \leq 0.05$ . All statistical analysis was completed using PASW (v18.0, SPSS Inc., Chicago, Illinois, USA).

## Results

### Aerobic Capacity and MAP

The  $\dot{V}O_{2MAX}$  and MAP values for each cycling cohort is presented in Table 1. Road cyclists possessed significantly higher  $\dot{V}O_{2MAX}$  ( $p=0.021$ ) than BMX cyclists. Both relative and absolute MAP measures in the road and XCMB cohorts were significantly greater than that of the DHMB and BMX cohorts.

### Anaerobic Capacity

The MAOD data are presented for both 60 s and 240 s efforts in Table 1 as a  $\dot{V}O_2$  equivalent (L), as well as a percentage (%) of total work contribution. The MAOD was

significantly higher for all cyclists when calculated across 60 s than 240 s ( $1.5 \pm 0.5$  L vs.  $-0.12 \pm 1.14$  L respectively,  $p < 0.001$ ). The road cyclists demonstrated significantly ( $p < 0.05$ ) greater MAOD and anaerobic contributions during both the 60 and 240 s efforts than the DHMB and BMX cohorts. However, the XCMB only demonstrated such a difference in the absolute MAOD across the 60 s effort.

### Power Output

Absolute and relative peak and mean power outputs from the PPA are presented in Table 2. No significant differences in peak power outputs were present between groups. Significant differences in absolute mean power output (W) were apparent between disciplines during efforts of 60 s, 240 s and 600 s. Relative mean power output (W·kg<sup>-1</sup>) was significantly different across disciplines during all efforts lasting longer than 5 s, as shown in Figure 1.

For all cyclists, strong relationships were present between  $\dot{V}O_{2MAX}$  and relative maximal mean power output (W·kg<sup>-1</sup>) during efforts lasting between 30-600 s ( $r=0.821-0.878$ ,  $p < 0.001$ ). Similarly, relative MAP (W·kg<sup>-1</sup>) was strongly correlated with maximal mean power output (W·kg<sup>-1</sup>) lasting 15-600 s ( $r=0.704-0.946$ ,  $p < 0.001$ ). Lastly, strong relationships were present between MAOD 60 s (L) and maximal mean power output (W·kg<sup>-1</sup>) for efforts lasting 15-600 s ( $r=0.743-0.771$ ,  $p < 0.001$ ).

## Discussion

The purpose of this study was to compare the physiological and performance characteristics of high-performance athletes across a range of cycling disciplines. The study presents the first laboratory-based time-power data that compares across road,

**Table 1.** Physiological characteristics (mean ± SD) of the various cycling disciplines taken from the incremental and power profile assessment.

	Road (n = 5)	XCMB (n = 9)	DHMB (n = 5)	BMX (n = 5)
<i>Parameter</i>				
Age (yr)	30 ± 7	30 ± 3	24 ± 6	23 ± 10
Height (cm)	183 ± 4	184 ± 6	183 ± 8	180 ± 4
Body mass (kg)	72.3 ± 3.5	79.1 ± 13.4	84.8 ± 6.6	81.3 ± 4.9
Σ7 Skinfolds (mm)	55 ± 14	62 ± 27	87 ± 31	76 ± 30
$\dot{V}O_{2MAX}$ (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	69.6 ± 11.5 <sup>b</sup>	65.3 ± 7.0	55.3 ± 6.1	52.4 ± 5.9
MAP (W)	452 ± 35 <sup>b</sup>	455 ± 35 <sup>b</sup>	400 ± 79	353 ± 48
MAP (W·kg <sup>-1</sup> )	6.3 ± 0.6 <sup>ab</sup>	5.8 ± 0.6 <sup>ab</sup>	4.7 ± 0.6	4.4 ± 0.7
MAOD 60 s (L)	1.80 ± 0.52 <sup>b</sup>	1.77 ± 0.38 <sup>b</sup>	1.31 ± 0.62	0.91 ± 0.06
MAOD 60 s (%)	30.8 ± 3.5	30.2 ± 5.3	25.3 ± 9.5	21.3 ± 2.6
MAOD 240 s (L)	0.90 ± 0.85 <sup>ab</sup>	0.23 ± 0.86	-1.04 ± 1.17	-0.94 ± 0.57
MAOD 240 s (%)	4.8 ± 5.4 <sup>ab</sup>	1.3 ± 5.2	-8.8 ± 10.5	-8.4 ± 5.4

Key: a = Different from DHMB ( $p \leq 0.05$ ); b = Different from BMX ( $p \leq 0.05$ ); BMX = Bicycle motocross cyclists; DHMB = Downhill mountain bikers; MAOD = Maximal accumulated oxygen deficit; MAP = Maximal aerobic power; n = Number of participants;  $\dot{V}O_{2MAX}$  = Maximal oxygen uptake; XCMB = Cross-country mountain bikers.

XCMB, DHMB and BMX cyclists, as well as some of the first data quantifying the aerobic and anaerobic capacities of these new off-road disciplines. Together, this data supports that significant differences are prevalent in physiological and power output measures across cycling disciplines, which may reflect natural selection within sports, or specific adaptation within continued training.

*Physiological characteristics*

The current data demonstrated that the road and XCMB cyclists possessed higher  $\dot{V}O_{2MAX}$  and MAP values than the DHMB and BMX cyclists. The reported  $\dot{V}O_{2MAX}$  values were comparable to national road and XCMB cyclists (Coyle et al., 1991; Gregory et al., 2007), but were lower than that reported for international level road and XCMB cyclists (Impellizzeri et al., 2005a; Lee et al., 2002; Padilla et al., 1999; Rodriguez-Marroyo et al., 2009). These data are in agreement with Wilber et al. (1997), who observed that national level road and XCMB cyclists displayed near-identical  $\dot{V}O_{2MAX}$  values. Conversely, Warner, Shaw and Dalsky (2002) and Lee et al. (2002), reported that well-trained and international level XCMB cyclists possess higher  $\dot{V}O_{2MAX}$  values than well-trained and international level road cyclists. However, it should be noted that in both of these studies, the XCMB cyclists possessed significantly lower body mass and body fat than the road cyclists, therefore resulting in higher relative  $\dot{V}O_{2MAX}$  values ( $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) for the XCMB cohort. These data indicate that competitive road and XCMB cyclists possess very high  $\dot{V}O_{2MAX}$  values that most likely reflect the increased training and competitive duration of these disciplines, which consist of longer efforts at sustainable intensities that consistently stimulate aerobic metabolism. Further, the data revealed that the BMX cyclists'  $\dot{V}O_{2MAX}$  values were significantly lower than the road cyclists; with a trend for DHMB and BMX cyclists to also possess  $\dot{V}O_{2MAX}$  values lower than XCMB cyclists. Importantly, the  $\dot{V}O_{2MAX}$  values for the DHMB and BMX cyclists were typical of age-matched recreationally active males, reflecting the low priority of aerobic development in these sports (Dalleck et al., 2004; Jacks et al., 2002). To date, no data has related  $\dot{V}O_{2MAX}$  to competition

**Table 2.** Peak and mean power output measures (mean  $\pm$  SD) during power profile assessment for various cycling disciplines.

	Effort Length (s)	Road (n = 5)	XCMB (n = 9)	DHMB (n = 5)	BMX (n = 5)
Peak power (W)	5 S	1135 $\pm$ 204	1148 $\pm$ 223	1059 $\pm$ 219	1331 $\pm$ 95
	5 R	1104 $\pm$ 146	1172 $\pm$ 259	1192 $\pm$ 200	1349 $\pm$ 108
	15	1058 $\pm$ 145	1155 $\pm$ 309	1203 $\pm$ 253	1247 $\pm$ 142
Peak power ( $\text{W}\cdot\text{kg}^{-1}$ )	5 S	15.7 $\pm$ 2.9	14.6 $\pm$ 2.2	12.4 $\pm$ 2.0	16.4 $\pm$ 1.1
	5 R	15.3 $\pm$ 2.0	14.8 $\pm$ 1.5	14.0 $\pm$ 1.4	16.6 $\pm$ 1.4
	15	14.6 $\pm$ 1.9	14.5 $\pm$ 1.7	14.1 $\pm$ 2.1	15.3 $\pm$ 1.5
Mean power (W)	5 S	852 $\pm$ 131	868 $\pm$ 183	802 $\pm$ 153	957 $\pm$ 131
	5 R	1046 $\pm$ 124	1106 $\pm$ 237	1078 $\pm$ 135	1183 $\pm$ 164
	15	900 $\pm$ 108	910 $\pm$ 160	851 $\pm$ 114	796 $\pm$ 95
	30	711 $\pm$ 125	698 $\pm$ 83	635 $\pm$ 125	524 $\pm$ 95
	60	518 $\pm$ 61 <sup>b</sup>	515 $\pm$ 34 <sup>b</sup>	435 $\pm$ 97	375 $\pm$ 57
	240	373 $\pm$ 76 <sup>b</sup>	366 $\pm$ 11 <sup>b</sup>	296 $\pm$ 96	212 $\pm$ 38
Mean power ( $\text{W}\cdot\text{kg}^{-1}$ )	5 S	11.8 $\pm$ 1.8	11.0 $\pm$ 1.5	9.4 $\pm$ 1.6	11.8 $\pm$ 1.2
	5 R	14.5 $\pm$ 1.7	13.9 $\pm$ 1.3	12.7 $\pm$ 1.0	14.6 $\pm$ 2.1
	15	12.5 $\pm$ 1.4 <sup>ab</sup>	11.5 $\pm$ 0.7	10.0 $\pm$ 1.0	9.9 $\pm$ 1.0
	30	9.8 $\pm$ 1.8 <sup>ab</sup>	8.9 $\pm$ 0.8 <sup>b</sup>	7.5 $\pm$ 1.2	6.4 $\pm$ 1.0
	60	7.2 $\pm$ 1.0 <sup>ab</sup>	6.6 $\pm$ 0.9 <sup>ab</sup>	5.1 $\pm$ 1.0	4.6 $\pm$ 0.6
	240	5.2 $\pm$ 1.1 <sup>ab</sup>	4.7 $\pm$ 0.7 <sup>b</sup>	3.5 $\pm$ 0.9	2.6 $\pm$ 0.3
	600	4.5 $\pm$ 0.8 <sup>ab</sup>	4.2 $\pm$ 0.5 <sup>ab</sup>	3.1 $\pm$ 0.9	2.2 $\pm$ 0.3

Key: a = Different from DHMB ( $p \leq 0.05$ ); b = Different from BMX ( $p \leq 0.05$ ); BMX = Bicycle motocross cyclists; DHMB = Downhill mountain bikers; n = Number of participants; R = Rolling standing start; S = Stationary standing start; XCMB = Cross-country mountain bikers.

requirements of DHMB and BMX, which may reflect the shorter (1–4 min), highly-intermittent nature of these disciplines. Recent data supports that DHMB cyclists may not stress their oxidative system during competition, as their  $\dot{V}O_2$  remains considerably low ( $23.1 \pm 6.1 \text{ mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ;  $52 \pm 14\% \dot{V}O_{2MAX}$ ) during DHMB competition (Burr et al., 2012; Hurst and Atkins, 2006). Importantly, it has been suggested that track-based sprint cycling lasting between 1-4 minutes may require between 50-84% contribution from aerobic energy production. However, the intermittent nature of DHMB and BMX disciplines is likely to alter this aerobic contribution during competition and present a limiting factor for ATP production (Craig et al., 1993; Medbo and Tabata, 1989). Previously, Tomlin and Wenger (2001) have reported that aerobic capacity may influence repeated sprint performance through allowing an increase in aerobic PCr resynthesis, which may potentially offer benefits to DHMB and BMX cyclists. The current results highlight important physiological differences in performance-matched cyclists across the various disciplines.

Separately, the MAP values of the road and XCMB cohorts were similar, and were comparable to values previously reported for national level road and XCMB cyclists (Baron, 2001; Ebert et al., 2006; Padilla et al., 2000; Wilber et al., 1997). Interestingly, the MAP values of these endurance-based disciplines were also similar to past reports of internationally competitive

road and XCMB cyclists (Impellizzeri et al., 2005a; Lee et al., 2002; Padilla et al., 2000; Wilber et al., 1997). However, the incremental exercise protocol used in the current study may have influenced this outcome, with such shorter protocols (~11-13 minutes) typically resulting in higher MAP values (Lucia et al., 2001). Furthermore, when expressed relative to body mass, differences in MAP were also apparent between the road and XCMB cyclists, as well as the DHMB and BMX groups. Collectively, the latter cohorts demonstrated a significantly lower relative MAP than the road and XCMB groups, which may reflect the higher body mass and similar absolute MAP values for the more sprint-orientated groups. This further supports the notion that aerobic characteristics are of little significance for DHMB or BMX racing, and that anaerobic characteristics and technical ability may be better at discriminating performance.

As expected, the current data supports strong relationships between  $\dot{V}O_{2MAX}$  and MAP across all cyclists ( $r=0.794-0.956$ ,  $p<0.001$ ).  $\dot{V}O_{2MAX}$  and MAP relative to body mass have been reported as an important characteristic for uphill road specialists and XCMB cyclists (Gregory et al., 2007; Lee et al., 2002; Padilla et al., 2000), however, this is some of the first research to report on the  $\dot{V}O_{2MAX}$  and MAP values of high-performing DHMB and BMX cyclists. The resulting data indicate that these characteristics are not highly developed as observed in endurance based cycling disciplines such as road or XCMB. Therefore, future research should continue to assess the relationship between measures of aerobic capacities and power against performance levels within these disciplines.

It is likely that a highly developed anaerobic capacity would be beneficial for cyclists of shorter-distance sprint-type disciplines such as DHMB and BMX. However, similar to the aerobic parameters discussed above, the road and XCMB cyclists attained higher MAOD values than the BMX cyclists across the 60 s effort. Further, across the 240 s effort, the MAOD of road cyclists was higher than both the DHMB and BMX cyclists, which may reflect that the latter cohorts do not complete constant high-intensity efforts of near-maximal intensity during any race situation. However, it may be that these cyclists only typically require intermittent short bursts of power, and as such, these cyclists could not sustain anaerobic power production over such duration (Cowell et al., 2011; Hurst and Atkins, 2006). Comparatively, the requirements of both road and XCMB cycling often requires prolonged high-intensity efforts throughout races that require a large proportion of anaerobic glycolysis for ATP production, which likely results in highly developed anaerobic capacities (Impellizzeri and Marcora, 2007; Lucia et al., 1999; Padilla et al., 2000). When expressed as a percentage of total work contribution, the road cyclists ( $4.8\pm 5.4\%$ ) completed a significantly higher percentage of the 240 s workload anaerobically than either the DHMB ( $-8.8\pm 10.5\%$ ,  $p=0.034$ ) or BMX ( $-8.4\pm 5.4\%$ ,  $p=0.041$ )

cyclists. Furthermore, negative MAOD values were calculated for nine of the ten DHMB/BMX cyclists during the 240 s effort, indicating that intensities reflective of anaerobic metabolism could not be sustained and that the cyclists reduced their exercise intensity to maximise ATP phosphorylation through aerobic metabolism. This data supports Craig et al. (1995) who reported such long duration efforts may not be suitable for the assessment of MAOD for sprint cyclists.

The current data demonstrated that the 60 s MAOD was significantly ( $p<0.001$ ) higher than the 240 s MAOD for all cyclists. This data opposes past data suggesting that the MAOD of endurance cyclists was more suitably assessed throughout longer-duration maximal efforts (300 s) (Craig et al., 1995). Furthermore, past research has reported high MAOD values

(~4.5 L) for elite endurance and sprint cyclists across both 2 min and 5 min maximal efforts (Craig et al., 1993). Comparatively, the cyclists of the current study demonstrated lower MAOD of  $1.5\pm 0.5$  L, which may reflect that the participants in the current study were not internationally competitive. Further, past tests have assessed MAOD of cyclists using isolated maximal exercise tests, rather than have such efforts built into a PPA. The increased aerobic metabolism may have occurred more quickly as a result of the reduction in metabolic inertia from the past efforts, which may have lowered the work completed with a reliance on anaerobic metabolism. As such, the data supports that road and XCMB cyclists possess high anaerobic capacities, with both DHMB and BMX cyclists appearing to be more reliant on phosphocreatine metabolism for their shorter maximal efforts. Further research is required to assess the relationship between anaerobic capacity and cycling performance across the various disciplines, to determine if this is a discriminative characteristic between competition levels.

#### *Power Output*

As previously highlighted, the use of laboratory-based PPA provides measures of sprint and endurance performance across a single protocol (Quod et al., 2010). To date, such assessments have only been reported for road cyclists, with the current data being the first to broaden the application of PPA protocols across other cycling disciplines. Importantly, the varied nature of the PPA protocol presents several measures that appear to differ between cycling cohorts.

No statistically significant differences in peak power output were present between any of the cycling disciplines within the current study. The values obtained for each discipline were consistent with peak power values reported for national level road cycling competitions ( $1119\pm 187$  W;  $16.1\pm 2.7$  W $\cdot$ kg $^{-1}$ ) (Ebert et al., 2006), as well as peak power outputs reported for elite national XCMB cyclists during a 10 s maximal laboratory test ( $14.9\pm 1.1$  W $\cdot$ kg $^{-1}$ ) (Baron, 2001). Further, Baron (2001) reported that such peak power

outputs were significantly higher than that produced by sport students who were non-cyclists ( $13.3 \pm 1.4 \text{ W} \cdot \text{kg}^{-1}$ ), demonstrating that such tests are valid measures for peak power production in high-performance cyclists. However, peak power output is likely to be of most importance for BMX cyclists where exceptionally high peak power outputs ( $\sim 2000 \text{ W}$ ; Herman et al., 2009) have been reported during field tests, although such values have not been reported within road, XCMB or DHMB disciplines. As such, effective training and performance management practices will differ between the disciplines, with BMX cyclists requiring significant development of leg strength and the PCr energy system to produce such high peak power outputs.

As expected, the road and XCMB cyclists produced similar mean power outputs across all maximal PPA efforts, which were similar to competitive road cyclists (Quod et al., 2009). Separately, XCMB produced slightly lower absolute and relative mean power outputs during the 30 s maximal effort ( $698 \pm 83 \text{ W}$ ;  $8.9 \pm 0.8 \text{ W} \cdot \text{kg}^{-1}$ ) than elite Olympic XCMB cyclists ( $741.4 \pm 39.6 \text{ W}$ ;  $10.7 \pm 0.5 \text{ W} \cdot \text{kg}^{-1}$ ) (Costa and Fernando, 2008). Similarly, Zabala et al. (2011) reported that elite BMX cyclists produced a mean output of  $809 \pm 113 \text{ W}$  during a 30 s Wingate test, while the current BMX cyclists only produced  $524 \pm 95 \text{ W}$ , however the adopted cycling position differed between these studies. Together, this strengthens the observation that such power output measures are discriminative indicators of performance. As expected,  $\dot{V}O_{2\text{MAX}}$ , MAP and MAOD were strongly and significantly correlated with maximal mean power output for all efforts lasting between 30 s and 600 s ( $r=0.704\text{--}0.946$ ,  $p<0.001$ ) for all cyclists. Despite these observations, this is the first data to report on the time-power relationship for XCMB, DHMB or BMX cyclists across maximal efforts of 5–600 s, hence the current data presents novel findings for the area. Therefore, future research is warranted to determine whether changes in the time-power relationship influences performance abilities across these disciplines.

As shown in Figure 1, the same PPA modelling approach was used across each cycling cohort. These power curves visually demonstrate the metabolic strengths and weaknesses of the various cycling cohorts with respect to changes in power output with effort duration that dictate the shape of the modelled curve. The road and XCMB cohorts produced a power profile curve that possessed a more gradual slope (as represented by the power exponents of  $-0.272$  and  $-0.277$ , respectively) due to their ability to maintain high aerobic power production during the longer efforts. Comparatively, the power profile curves of the highly sprint-focused BMX ( $-0.426$ ) and DHMB ( $-0.326$ ) cyclists demonstrated power exponents that were considerably higher than shown for the endurance-based cyclists. Such differences in the power exponent of the fitting models demonstrated that the different cycling cohorts had different rates of decline in power output as duration increased. For example, when effort duration was doubled, the

exponent for the BMX cyclists suggests that power output was reduced by 26%, whereas the other disciplines were characterised by much smaller reductions in power output in response to effort duration (DHMB: 20.3%, XCMB: 17.5% and road 17.2% cyclists). Hence, the BMX cyclists' PPA curve shows an exceptionally steep slope as the cyclists were capable of producing high anaerobic power across short durations (5 s) but could not sustain high power output for efforts that were more dependent on aerobic metabolism ( $\geq 15 \text{ s}$ ). As such, while PPA curves have been effectively used within the performance testing of road cycling (Quod et al., 2010), there is further scope of application in the interpretation of the resultant power equation. The components of the power function used to fit the PPA curve can be interpreted to quantify changes in the metabolic capacities of a cyclist that are responsible for limiting physiological function. Such detailed analysis could also be further utilised to identify the metabolic strengths and weaknesses of a cyclist in talent identification or monitoring cross-seasonal performance throughout a range of cycling disciplines.

It should be noted that there are several limitations to the current study, such as the relatively low number of participants, however, increasing the recruitment of participants outside the high performance level would have reduced the homogeneity of the cohorts. Furthermore, the recruited cyclists were at varying stages of their respective competitive seasons during the testing period, however, it was not feasible to align testing across each competitive season.

## Conclusions

This study has demonstrated that high-performance road and XCMB cyclists possess similar characteristics, which differ greatly to both DHMB and BMX cyclists. Importantly, the current road and XCMB cyclists possessed significantly higher aerobic and anaerobic capacities as well as power outputs across maximal efforts lasting 15–600 s. Interestingly, the DHMB and BMX athletes were physiologically inferior to the road and XCMB cohorts for longer efforts ( $>5 \text{ s}$ ), which most likely reflects the requirements of training and competition. Both DHMB and BMX cyclists may be more reliant on strength, PCr metabolism and technical abilities for success. Overall, this research provides new and novel comparative information on the physiological capacities and power output characteristics of the various cycling disciplines.

## Practical applications

This study presents some of the first data identifying key physiological and performance characteristics of off-road cyclists such as aerobic and anaerobic capacities as well as power output characteristics. The data highlights the use of PPA across a range of cycling disciplines and that there are significant differences between each of the cycling disciplines. As such, coaches should be aware that training practices should be tailored specifically to meet the unique requirements of each separate discipline.

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