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Examining pacing profiles in elite female road cyclists using exposure variation analysis

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ABSTRACT

Objective In this study, the amplitude and time distribution of power output in a variety of competitive cycling events through the use of a new mathematical analysis was examined: exposure variation analysis (EVA).

Design Descriptive field study.

Setting Various professional road cycling events, including; a 5-day–eight-stage tour race, a 1-day World Cup event and the Australian National Individual Time Trial Championships.

Participants 9 elite female cyclists (mean (SD), mass = 57.8 (3.4) kg, height = 167.3 (2.8) cm, Vo_2peak = 63.2 (5.2) ml kg^{-1} min^{-1}).

Interventions None.

Main outcome measurements The variation in power output and the quantification of the total time and acute time spent at various exercise intensities during competitive professional cycling were examined. Predefined levels of exercise intensity that elicited first ventilation threshold, second ventilation threshold and maximal aerobic power were determined from a graded exercise test performed before the events and compared with power output during each event.

Results EVA exposed that power output during the time trial was highly variable (EVA_{SD} = 2.81 (0.33)) but more evenly distributed than the circuit/criterium (4.23 (0.31)) and road race events (4.81 (0.96)).

Conclusion EVA may be useful for illustrating variations in the amplitude and time distribution of power output during cycling events. The specific race format influenced not only the overall time spent in various power bands, but also the acute time spent at these exercise intensities.

Ebert *et al*[1] recently documented the percentage of overall performance time spent in various power bands during women's flat and hilly World Cup professional races. In this study, it was found that the racing terrain may have influenced the power output profiles in these cyclists, as a greater percentage of time was spent above 500 W and between 100 and 300 W during flat and hilly races, respectively.[1] While this analysis provides valuable information regarding the overall power output distribution during such events, comprehensive analysis of the acute time spent in various power bands has not been explored. In addition, the minor fluctuations in power output often observed during cycling are poorly understood. It is believed that these minor fluctuations in power output may be related to a central regulation of exercise intensity.[2 3] However, the fundamental mathematical techniques used to quantify variation in these studies fail to expose important aspects of variation. For instance, it has previously been found through the use of discrete Fourier transformation that dominant power frequency bands may exist,[3] which may be cycling task specific.[2 3] However, in these studies, the use of Fourier transformation only quantifies the degree of variation and is not sensitive to changes in amplitude, frequency and time.

Exposure variation analysis (EVA) is an analytical method developed to quantify acute and cumulative physical load exposure in ergonomic research.[4] For example, Straker *et al*[4] have recently used EVA to examine musculoskeletal stress in children during various administrative tasks and found that both posture and muscle activity were less variable/more monotonous when working with computers, compared with books, pens and paper. Briefly, EVA is an analytical technique that describes the total duration as well as the intermittent or acute time spent at predefined exercise intensities. An advantage of EVA over previously used analytical techniques[2 3 5] is that EVA examines not only the cumulative race time spent at various exercise intensities (ie, >500 W) but also the duration that these exercise intensities were maintained for. It is therefore possible that EVA may provide a more comprehensive indication of the variation in power output and the work-to-rest ratios experienced during cycle racing.

The purposes of this study were to (1) examine the amplitude and time distribution of power output of elite-level female road cyclists performing in a variety of competitive cycling events through the use of EVA and (2) examine the relationship between physiological variables measured during a graded exercise test and field-based elite cycling performance.

METHODS

Subjects

Race data were collected from a total of nine elite female cyclists (mean (SD), mass = 57.8 (3.4) kg, height = 167.3 (2.8) cm, Vo_2peak = 63.2 (5.2) ml kg^{-1} min^{-1}) performing in a 5-day–eight-stage tour race, a 1-day World Cup event and the Australian National Individual Time Trial Championship (described below). Subjects were classified as "elite" based upon their physiological characteristics,[6] training status and previous race performance.[7 8] Before the events, subjects provided written informed consent in accordance with the Human Research Ethical Committee of the Australia Sports Commission.

Laboratory data collection

Before competing in the events, each subject performed a graded maximal exercise test on an

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electromagnetically braked cycle ergometer (Lode Excalibur, Groningen, The Netherlands). The test commenced at a power output of 125 W and increased by 25 W every 3 min until volitational exhaustion.[8] Respiratory gases were measured throughout the incremental test using a calibrated customised gas analysing system (Australian Institute of Sport, Canberra, Australian Capital Territory, Australia). Vo_2peak was defined as the average of the two highest consecutive 30-s samples. Maximal aerobic power (MAP) was calculated in a pro rata manner and calculated via the following equation:

$$MAP = (W_L)+[(t/3)\times 25][9]$$

where W_L refers to the power output (W) of the last stage completed, and t is the amount of time (min) that was competed in the incomplete workload.

The workloads (W) corresponding to the first and second ventilation threshold (VT_1 and VT_2, respectively) were determined via previously described methods.[10] The calculation of the power output corresponding to VT_1, VT_2 and VO_2peak (MAP) allowed the determination of four levels of exercise intensity; these include phase I (<VT_1), II (VT_1 to VT_2), III (VT_2 to MAP) and IV (>MAP).[5] A further three levels were determined based upon the SE of measurement in power output at VT_1 (6.9%), VT_2 (4.5%) and MAP (3.0%).[11] These power output ranges were then compared with power outputs recorded during each field event (described below).

Field data collection

Before each event, the subject's bicycle was fitted with a professional model SRM power metre (Schoberer Rad Mebtechnik, Julich, Germany), which recorded power output, cadence and speed every second. Overall performance times of all cyclists were retrieved from the official race timing results following each event. The environmental conditions of each race were retrieved from the Bureau of Meteorology following the events.

5-Day–eight-stage road race (Tour de Snowy)

The 2001 Tour de Snowy was an eight-stage road race (449.4 km) held in the Snowy Mountains of New South Wales, Australia, performed over five consecutive days (3–7 March 2001). During this event, cyclists participated in three short-circuit/criterium events (~30 km) and five short-distance to mid-distance road races (35–110 km). The race involved a total of five mountain passes, four of which were classified as category 2 and one of which was classified as a category 1. In total, 71 cyclists from 15 teams started the event, and 61 cyclists completed the race. Data were collected from six cyclists who competed in two separate teams. Throughout the event, ambient air temperature ranged from 11° to 28.6°C (19.6 (5.9)°C), and relative humidity ranged from 98% to 29% 58 (25%). Wind speed was recorded to be between 0 and 20 km h^{-1} (8.1 (5.9) km h^{-1}) during the event.

UCI World Cup event

The Union Cycliste Internationale (UCI) Women's World Cup Race was a 1-day event held in Canberra (ACT) on 10 March 2001. This World Cup event was the first in a series of nine races that made up the 2001 UCI World Cup Series. This event involved a 102-km race performed over 20 flat (~40-m elevation change) 5.1-km laps. In total, 68 cyclists from 15 teams started the event, and of those cyclists, 51 of them completed the race. Data were collected from six cyclists who competed in three separate teams. At commencement of the race, ambient air temperature was 18°C, relative humidity was 76% and wind speed was 7.6 km h^{-1}.

Individual road time trial

The women's Australian National Road Time Trial Championship was conducted in Canberra, Australia on 11 March 2001 and involved a 24.2-km individual cycle time trial performed over two flat (<10-m elevation), equal distance laps (12.1 km). Data were collected on six cyclists. Upon commencement of the event, ambient air temperature was 18°C, relative humidity was 46% and wind speed was 13 km h^{-1}.

Exposure variation analysis

The quantification of the total time and acute time spent at various exercise intensities during all events was expressed using EVA[12] and analysed using customised software written in Labview (National Instruments Corporation, Austin, Texas, USA). The EVA program developed for this study expresses power output during the various events as a tridimensional distribution. In short, EVA was used to separate field-based cycling power output into both time and amplitude domains. As with previous research,[1 5] EVA quantified the percentage of overall race time (ie, cumulative time) that was spent within predefined levels of exercise intensity (ie, phase I to phase IV). In addition to this, EVA was also used to quantify the duration or length of time for which power output was maintained within each predefined level of exercise intensity (ie, acute time), without changing to another power band/level. For the purpose of this study, the overall time spent in each power band has been referred to as the "cumulative" or percentage of overall race time. The period for which power output was maintained in each power band, without changing to another power band, has been referred to as the "acute" time. To correspond with previous research,[1 5] the levels of exercise intensity used in this study (ie, x axis; fig 1B) were based upon the power output corresponding to VT_1, VT_2 and MAP (table 1). The percentage of overall race time (z axis; fig 1B) and the acute time (y axis; fig 1B) spent at these exercise intensities were determined. The duration of each acute time band was determined based upon the hyperbolic relationship between power output and time to exhaustion.[13] Briefly, the duration of each acute time band was increased by a factor of two (ie, 1.875, 3.75, 7.5, 15 and 30 s). The duration of the longest acute time band (30 s) was chosen to be similar to the duration of a typical cycling anaerobic test.[14] Average EVA plots were then calculated by grouping data into an individual time trial (Australian National Time Trial), circuit/criterium events (total of four stages/events) and short-to-middle distance road races (total of five stages).

Statistical analyses

Data are reported as means (SDs) unless otherwise specified. Average power output and planned comparisons of particular intensity/duration bands during the various events were compared using a one-way repeated measure ANOVA. To statistically assess the variations in power output during the various events, the SD of the EVA matrix (EVA_{SD}) was calculated and compared using a one-way repeated measure ANOVA.[4 15] A greater EVA_{SD} indicates that more time is spent within particular intensity/duration band, which therefore reflects greater monotony or less-even dispersion of power output.[4]

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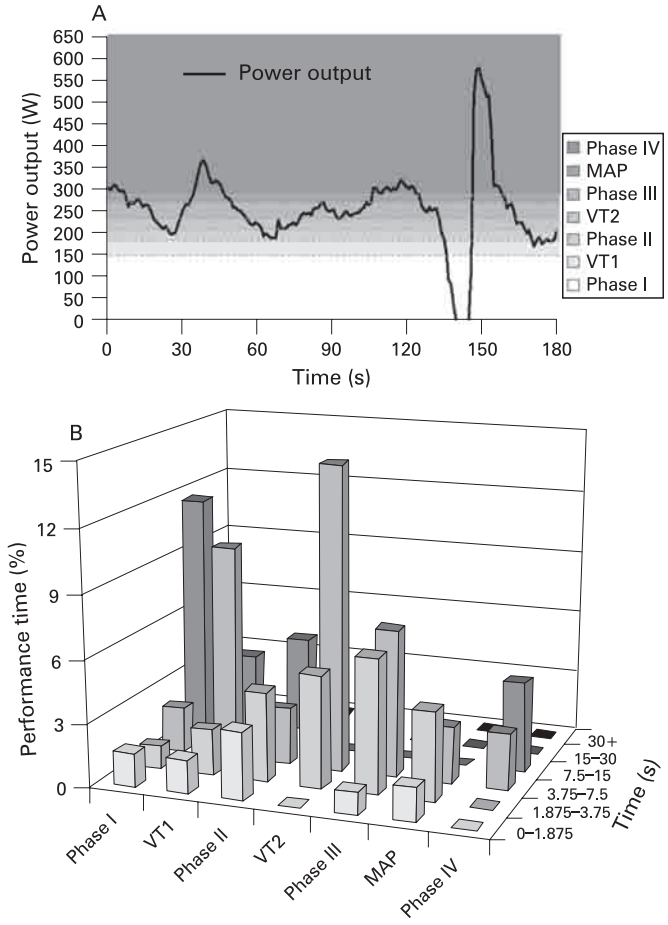

Figure 1 Example of raw power output (A) and its exposure variation analysis plot (B) for a single subject during a 3-min portion of the individual time trial.

A Pearson product moment correlation coefficient was used to determine relationships between average power output during the various events and physiological variables determined from the graded exercise test (ie, Vo_2peak, MAP and the power output corresponding to VT_1 and VT_2). A Pearson product moment correlation was also used to determine the relationship between performance during the various events (ie, time trial, circuit/criterium and road race events) and the percentage of race time spent at various exercise intensities. Confidence limits (CL) were determined with the use of an Excel spreadsheet created by Hopkins.[16] All other statistical tests were conducted using SPSS V.14.0 (Chicago, Illinois, USA) and acceptance of statistical significance was set at $p<0.05$.

RESULTS

The power outputs corresponding to the various exercise intensities (ie, VT_1, VT_2 and MAP) are shown in table 1. Average performance times and power outputs during the competition events are shown in table 2. Average power output during the time trial was significantly greater than both the circuit/criterium and road race events ($p<0.05$), but no differences were found between the circuit/criterium or road race events (table 2). Average EVA plots for subjects performing in the time trial, circuit/criterium and road race events are shown in fig 2. From analysis of the EVA matrix, it can be seen that the distribution of power output during the time trial is highly variable ($EVA_{SD} = 2.81$ (0.33)) but more evenly distributed compared with the circuit/criterium (4.23 (0.31); $p = 0.009$) and road race events (4.81 (0.96); $p = 0.001$; fig 2). The EVA_{SD} was also significantly different between the circuit/criterium and road race events ($p = 0.041$). Compared with the time trial, a significantly greater percentage of race time was spent either below VT_1 (phase I) or above MAP (phase IV) during both the circuit/criterium and road race events ($p<0.05$; fig 3A). In contrast, a significantly greater percentage of race time was spent at phase 2 and VT_2 during the time trial, compared with both the circuit/criterium and road race events ($p<0.05$; fig 3A). The percentage of race time spent within set power bands for greater than 15 s was significantly different among the time trial, circuit/criterium and road race events ($p<0.05$; fig 3B). The percentage of race time spent within set power bands for 3.75 to 7.5 s was significantly less during the road race, compared with the time trial and circuit/criterium events ($p<0.05$; fig 3B).

Table 1 Power output (W) corresponding to the various intensity bands used for exposure variation analysis (n = 9)

	Lower	Upper
Phase I ($<VT_1$)	0	205 (12)
First ventilation threshold (VT_1)	205 (12)	235 (14)
Phase II (VT_1 to VT_2)	235 (14)	253 (19)
Second ventilation threshold (VT_2)	253 (19)	278 (20)
Phase III (VT_2 to MAP)	278 (20)	296 (24)
Maximal aerobic power (MAP)	296 (24)	314 (26)
Phase IV (>MAP)	314 (26)	∞

MAP, maximal aerobic power; VT_1, first ventilation threshold; VT_2, second ventilation threshold; ∞, infinity.

The absolute power output (W) corresponding to Vo_2peak (MAP) and VT_2 was significantly correlated with average power output during the time trial ($r = 0.96$; $p = 0.011$; 95% CL = 0.67 to 1.00, and $r = 0.93$; $p = 0.024$; 95% CL = 0.48 to 0.99, respectively) and the circuit/criterium events ($r = 0.92$; $p = 0.009$; 95% CL = 0.43 to 0.99, and $r = 0.93$; $p = 0.007$; 95% CL = 0.48 to 0.99, respectively). No other physiological variables measured during the graded exercise test were significantly correlated with average absolute power output during the time trial, circuit/criterium and road race events. Average power output during the road race was significantly correlated with the percentage of overall race time spent at MAP ($r = 0.89$; $p = 0.019$; 95% CL = 0.28 to 0.99) and negatively correlated with the percentage of race time spent at VT_1 ($r = -0.83$; $p = 0.41$; 95% CL = −0.98 to −0.06). Average power output during the time trial was significantly correlated with the percentage of overall race time spent at phase II ($r = 0.86$; $p = 0.026$; 95% CL = 0.16 to 0.98) and negatively correlated with the percentage of race time spent in the acute time band of 0–1.875 s ($r = -0.93$; $p = 0.007$; 95% CL = −0.99 to −0.48).

DISCUSSION

The purposes of the present study were to (1) investigate the power output distribution of elite-level female road cyclists performing in a variety of competitive cycling events through the use of EVA and (2) examine relationships between laboratory-based physiological variables and performance during competitive elite female cycling. The major finding from this study was that the specific race format influenced not only the overall time spent in various power bands but also the acute time spent at these exercise intensities.

The overall distribution of exercise intensity during the circuit/criterium events and road race events observed in this study (fig 3A) are comparable to that previously reported in

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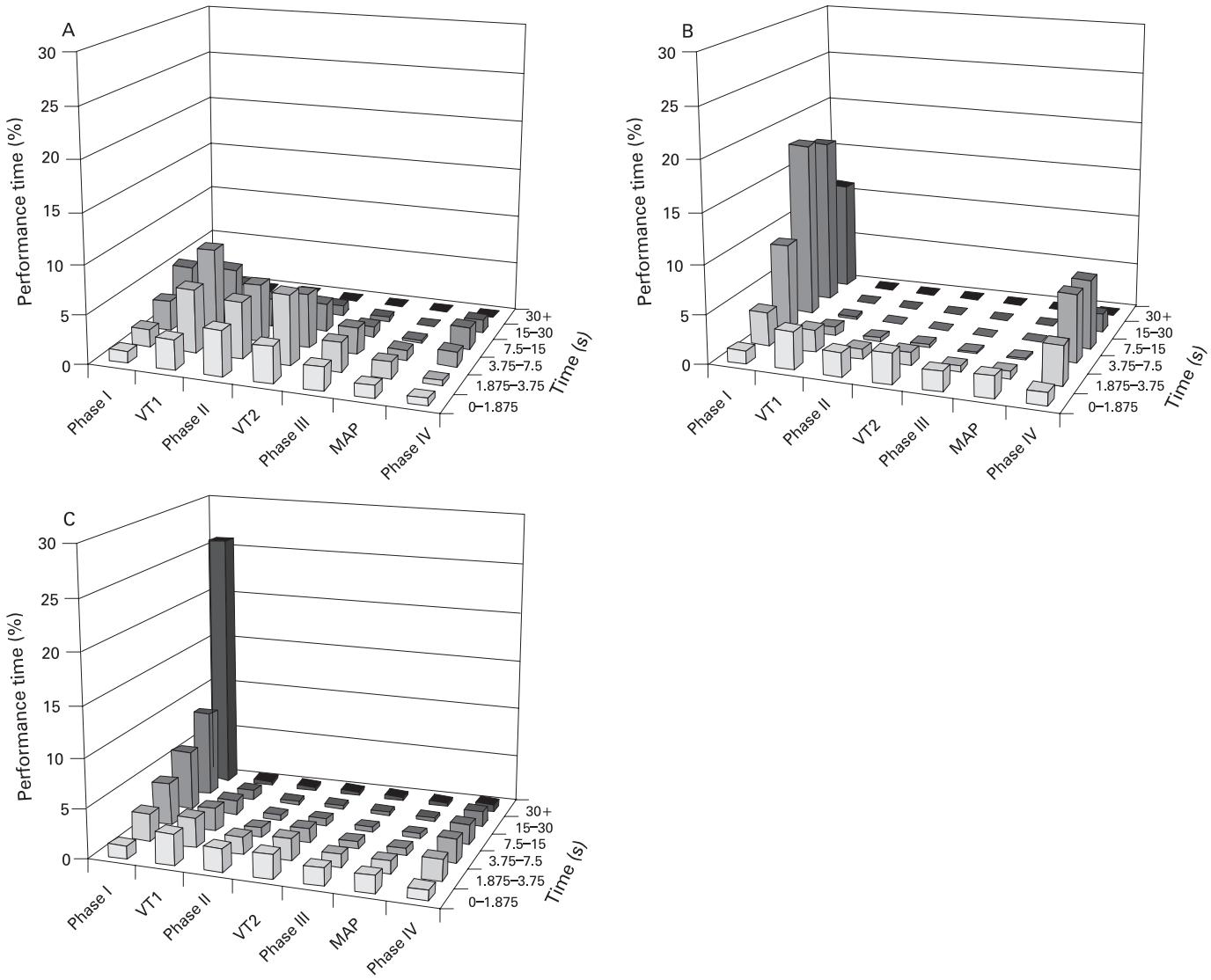

Figure 2 Average exposure variation analysis plots of power output for subjects (n = 6) during (A) an individual time trial event, (B) short-circuit/criterium events and (C) short-to-middle distance road race events.

mountainous/hilly stages of both male[5] and female[1] cycling events. Similarly, the average power output during the circuit/criterium and road race events (~170 W; table 2) is similar to that previously observed during a Women's UCI World Cup road cycling event that was performed over hilly terrain (169 (17) W).[1] However, during the time trial, the distribution of power output relative to the subject's individual physiological variables (ie, VT_1, VT_2 and MAP) was considerably lower than that which has previously been reported in professional male cyclists.[5] Lucia *et al*[5] found that during the Tour de France, professional male cyclists perform more than 50% of their individual time trials at intensities above the second ventilation threshold (>phase III). In the present study, however, subjects only held intensities above second ventilation threshold for ~20% to 40% of the total time trial duration. Differences observed between these two studies may be due to differences in the methodologies used to assess exercise intensity. Indeed, Lucia *et al*[5] examined the heart rate response of their elite cyclists during competition and compared this with heart rates obtained from an incremental exercise test. While the use of heart rate may provide detailed information regarding the overall physiological stress experienced during such events,[5 17–19] it is possible that factors such as a delayed heart rate response to rapid changes in exercise intensity coupled with cardiovascular drift could result in an overestimation of the exercise intensity found in the Lucia *et al* study.[20]

In the present study, power output during the various events was found to be highly variable. Indeed, the acute time spent in the moderate-to-high exercise intensity power bands (ie, $>VT_1$) was extremely short (<15 s), irrespective of the racing format (fig 2). It is likely that such variable power outputs observed during the various events of the present study are a reflection of the variable external "field" conditions, such as wind, terrain and race dynamics. Increasing power output uphill and into headwinds and reducing power output during downhill and tailwinds sections may improve overall performance times during endurance cycling events.[21 22] Thus, the variations in power output observed during the time trial event in the present study may have occurred in response to varying external conditions. During the circuit/criterium and road race events, however, race dynamics would have likely become increasingly more influential on the variability of pace observed during the event. During circuit/criterium and road race events, very little time was spent at exercise intensities between VT_1 and MAP

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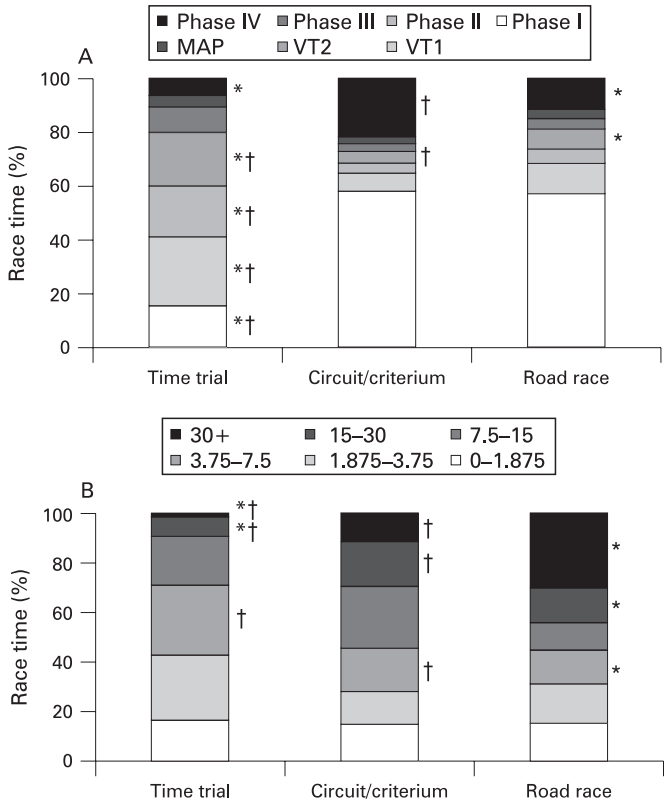

Figure 3 Percentage of overall race time spent at various exercise intensity zones (A) and the percentage of overall time spent in various acute time bands (B) during the individual time trial (TT), short-circuit/criterium (CC) events and road race (RR) events. MAP, maximal aerobic power; VT_1, first ventilation threshold; VT_2, second ventilation threshold. *p<0.05 vs CC; †p<0.05 vs RR.

(~20% and 30%, respectively), and when these power outputs were reached, they were only held for extremely brief periods (<3.75 s; fig 2B and C). Instead, the majority of time during the circuit/criterium and road race events was spent either below VT_1 (phase I) or above MAP (phase IV). As a result, power output was more evenly distributed during the time trial compared with the circuit/criterium and road race events (fig 2). These results highlight the highly variable, dynamic and irregular nature of mass-start, elite female road cycling events. Further, these results raise an important issue regarding the practical application of data from this study. Indeed, it is well established that intermittent exercise may increase the development of fatigue[23] and therefore be more detrimental to performance when compared with a continuous power output. However, it has also been suggested that the minor variations in power output that occur during self-paced cycling are associated with a central regulation of exercise intensity aimed at preventing the development of fatigue.[3] Whether or not it is advantageous for power output to be more or less variable is beyond the scope of this paper. However, future research may be able to use EVA to examine and ascertain the influence of minor variations in power output on performance during cycling.

Table 2 Average power output and performance time during the individual time trial, short circuit/criterium and short-to-middle distance road race events

	Time trial	Circuit/criterium	Road race
Power output (W)	248 (13)	174 (13)*	170 (10)*
Performance time (min)	34.5 (0.9)	76.3 (11)	135.4 (7.6)

*p<0.05 vs time trial.

What is already known on this topic

- Power output during competitive cycling may be highly variable and dependent on the specific racing terrain.
- Further, previous research using discrete Fourier transformation has found that that dominant power frequencies bands may exist and be cycling task specific, although Fourier transformation is limited and not sensitive to changes in amplitude, frequency and time.

What this study adds

- Exposure variant analysis may be a useful tool for quantifying variations in the amplitude and time distribution of power output during cycling.
- The use of such research may enhance our understanding of the physiological demands of competitive cycling events and thus assist in the development of training programs, sports-specific testing and talent identification for cycling.

As previously mentioned, power outputs that occurred between VT_1 and MAP were only maintained for brief periods (<3.75 s) during the circuit/criterium events. This likely is a reflection on the fact that athletes in the present study are often required to explosively produce, and rapidly recover from, high power outputs (≥MAP) during circuit/criterium events. Indeed, overall performance during the circuit/criterium events (table 2) was significantly correlated with the power output corresponding to Vo_2peak (ie, MAP) determined from the graded exercise tests. While overall performance during the road race events was correlated with the percentage of race time spent at MAP, average power output during the road race events was also negatively correlated with the percentage of race time spent in the acute time band of 0 to 1.875 s. Therefore, it seems that performance during road race events is not necessarily dictated by the ability to rapidly produce power, but may instead be influenced by the percentage of overall race time spent at high power outputs (ie, >MAP). During the road race events in the present study, athletes were often required to ascend through long and difficult mountain passes at influential stages of the race. Therefore, the ability to produce high power outputs for prolonged periods was of increasing importance to overall road race performance in this particular case.

In conclusion, results of the present study have indicated that EVA may be a useful tool for quantifying variations in the amplitude and time distribution of power output during cycling events. Consequently, EVA may be able to assist researchers in the future with their understanding of the physiological demands of competitive cycling events. Such research may then be used to assist athletes, coaches and researchers with the development of training programs, sports-specific testing and talent identification. In this study, power output distribution was found to be highly variable and to differ among various professional female cycling events. Power output during an individual time trial was highly variable but more evenly distributed compared with short-circuit/criterium events and short-to-middle distance road race events.

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Competing interests None.

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