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ORIGINAL ARTICLE

Maximal torque- and power-pedaling rate relationships for elite sprint cyclists in laboratory and field tests

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Abstract Performance models provide an opportunity to examine cycling in a broad parameter space. Variables used to drive such models have traditionally been measured in the laboratory. The assumption, however, that maximal laboratory power is similar to field power has received limited attention. The purpose of the study was to compare the maximal torque- and power-pedaling rate relationships during ''all-out'' sprints performed on laboratory ergometers and on moving bicycles with elite cyclists. Over a 3-day period, seven male (mean ± SD; 180.0 ± 3.0 cm; 86.2 ± 6.1 kg) elite track cyclists completed two maximal 6 s cycle ergometer trials and two 65 m sprints on a moving bicycle; calibrated SRM powermeters were used and data were analyzed per revolution to establish torque- and power-pedaling rate relationships, maximum power, maximum torque and maximum pedaling rate. The inertial load of our laboratory test was (37.16 ± 0.37 kg m^2), approximately half as large as the field trials (69.7 ± 3.8 kg m^2). There were no statistically significant differences between laboratory and field maximum power (1791 ± 169; 1792 ± 156 W; P = 0.863), optimal pedaling rate (128 ± 7; 129 ± 9 rpm; P = 0.863), torque-pedaling rate linear regression slope (–1.040 ± 0.09; –1.035 ± 0.10; P = 0.891) and maximum torque (266 ± 20; 266 ± 13 Nm; P = 0.840), respectively. Similar torque- and power-pedaling rate relationships were demonstrated in laboratory and field settings. The findings suggest that maximal laboratory data may provide an accurate means of modeling cycling performance.

Keywords Cadence · Power · World-class · Track cycling · Fitness testing

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Introduction

Maximal cycling torque- and power-pedaling rate relationships have been the focus of numerous laboratory-based investigations (Sargeant et al. 1981; McCartney et al. 1983; Vandewalle et al. 1985; Linossier et al. 1993; Martin et al. 1997). The authors of these studies have generally reported a linear torque-pedaling rate relationship and a quadratic power-pedaling rate relationship. Similar relationships have been found using a variety of techniques including isokinetic (Sargeant et al. 1981), force–velocity (Vandewalle et al. 1985) and inertial load cycling tests (Martin et al. 1997). In each of these tests, subjects were usually seated and in order to avoid metabolic fatigue, the trials were short (e.g., <6 s).

Recently, we reported that bicycle speeds could be accurately predicted from known power–time data during all-out maximal power, non-steady state cycling using valid portable power monitoring equipment (Gardner et al. 2004; Martin et al. 2006). A natural application of this modeling technique is predicting of actual cycling performance based on laboratory-measured power, pedaling rate and fatigue data. Prior to attempting such modeling, it is first necessary to establish the agreement between laboratory-based torque- and power-pedaling rate relationships and similar data collected while cycling on a moving bicycle.

Some of the highest values of maximal cycling power values are produced by cyclists who compete in the match sprint and 500 m and 1000 m time trial events (Dorel et al. 2005; Gardner et al. 2005). The characteristics of these cycling events differ in several ways from traditional laboratory-based power tests; during competition, elite sprint cyclists use large gear ratios, which require more time and work to accelerate to high pedaling rates than traditional laboratory-based fatigue-free protocols (Martin et al. 1997). Furthermore, the athletes must balance and control a moving bicycle while producing maximal power. Finally, sprint cyclists generally assume a standing position during the acceleration phase, which is known to allow greater power production (Reiser et al. 2002). Consequently, the extent to which torque- and power-pedaling rate relationships derived in the laboratory accurately characterize the maximal capabilities during actual sprint cycling performance remains unknown.

The aim of the present study was to compare the maximal torque- and power-pedaling rate relationships produced by elite male sprint cyclists during laboratory testing and velodrome cycling. We hypothesized that due to the aforementioned differences between field sprint performance and traditional laboratory tests, different torque-pedaling rate relationships would result.

Methods

Seven male cyclists (180.0 ± 3.0 cm; 86.2 ± 6.3 kg) volunteered to participate in the study. All cyclists were members of the Australian track cycling team and had recently represented Australia at either the senior or junior world track championships. The cyclists gave written informed consent prior to participating in the study, which had been approved by the Australian Institute of Sport ethics committee. Testing sessions were separated by 1 day and each cyclist's maximal sprints were performed at approximately the same time of the day. Cyclists were asked to avoid caffeine and food for 4 h prior to testing and to avoid intense exercise in the 12 h before each session. All cyclists used their own cycling shoes and pedals in both trials.

Both laboratory and field test protocols (test duration, warm-up, standing position and power measurement) were standardized and reflected pre-competition scenarios. Laboratory power testing was performed on an SRM cycle ergometer (Schoberer Resistance Mechanism, Germany) fitted with a dynamically calibrated scientific (20 strain gage) version SRM powermeter (Gardner et al. 2004); the ergometer was fitted with a large flywheel (8.44 kg). The warm-up for the laboratory test included 15 min of low-intensity cycling followed by three short (3–5 s) maximal sprints on an air-braked ergometer, each separated by at least 3 min recovery. After 10 min following the warm-up, the cyclists performed two maximal 6 s sprints from rest in a standing position. The test was similar to the inertial load cycling test described previously by Martin et al. (1997), except that the inertial load of 37.16 kg m^2 was much larger (see inertial load calculation below). The ergometer geometry (seat height and handlebar position in relation to the crank center) was matched to the athlete's bicycle, which they used in the field trials, and the SRM powermeter was zeroed before each test in accordance with the manufacturer's instructions. Data were recorded at 5 Hz, which produced values that represent one-revolution averages (MacIntosh et al. 2004).

For the field tests, each athlete's bicycle was fitted with a dynamically calibrated (Gardner et al. 2004) professional version (4 strain gage) SRM powermeter. Body mass was measured before the trials using calibrated (10–120 kg) portable electronic scales (Model UC-300, AND, Japan). The field warm-up consisted of 5 km of sub-maximal cycling and three short sprints. The field tests involved two all-out sanding-start 65 m sprints, each separated by at least 3 min recovery. The gear ratio used was 48 (front)/14 (rear), which produced inertial loads of 69.7 ± 3.8 kg m^2 (see inertial load calculation below). The SRM power-control units recorded power at 5 Hz and were zeroed prior to each trial.

We defined inertial load as $\frac{1}{2}IG^2$ where I is the moment of inertia of the flywheel and G is the gear ratio (Martin et al. 1997). For the laboratory test, the primary gear ratio was 53 (front)/17 (rear). Because of the complexity of the SRM flywheel system, its moment of inertia (I) was estimated by setting the rate of change of kinetic energy equal to 95% (a value to represent assumed frictional losses in the drive system of 5%) of the measured power: $0.95 \times \text{average power} = (1/2 \times \omega_f^2 - 1/2 \times I \times \omega_i^2)/(t_f - t_i)$. That equation can be rearranged to form an expression for moment of inertia: $I = 1.9 \times \text{Power} \times \Delta t/(\omega_f^2 - \omega_i^2)$ where angular velocity of the ergometer flywheel system (ω), was calculated from the recorded speed, assumed flywheel size, and gear ratio of the intermediate drive, 90/32. Using this technique, we determined that the moment of inertia was 6.18 ± 0.06 kg m^2. Based on this value for flywheel moment of inertia, the inertial load of the ergometer was estimated to be 37.16 ± 0.37 kg m^2. These data were only used as reference values for comparison and were not used in our calculation of power.

An equivalent moment of inertia for the bicycle/rider system was estimated as $I = mr^2$, where m is the combined mass of the bicycle and rider (in full racing outfit) and the mass of two additional tires and rims, and r is the outside radius of the bicycle tire (0.333 m). In order to take into account the fact that the wheels have both linear and rotational inertia, the mass of the rim and tire and tube were accounted for twice. That inertia and the bicycle gear ratios were used to calculate the inertial load of 69.7 ± 3.8 kg m^2, approximately twice as large as the load used in our laboratory trials and up to seven times as large as the load previously used by Martin and colleagues (Martin et al. 1997).

Data analysis

Torque (T) was calculated from the power (P) and pedaling rate (PR) data recorded by the SRM powermeter: $T = P/(\mathrm{PR} \times \pi/30)$, where P is in units of watts, T is in Nm and PR is in rpm. Linear regression analyses were then undertaken to determine the torque-pedaling rate relationships for laboratory and field trials. In order to match the pedaling rate range as best as possible between conditions, the torque-pedaling rate regression was constructed from the first 4 s of the laboratory test data and 7 s of the field test data. Because the SRM gives repeated values for power when the sampling rate is greater than the pedaling rate, all repeated values obtained from the SRM download were removed to avoid bias in the regression. A representative plot showing the linear nature of one subject's data can be observed in Fig. 1.

The torque intercept of these regression equations represented maximum torque (T_{max}) and the pedaling rate intercept represented maximum pedaling rate (PR_{max}). The well-known linear decrease in torque with increasing pedaling rate gives rise to a quadratic power-pedaling rate relationship in which the apex occurs at half the PR_{max} (Sargeant et al. 1984). The optimal pedaling rate was therefore calculated as $\mathrm{PR}_{max}/2$ and maximum power as $T_{max} \times \mathrm{PR}_{opt} \times \pi/30$. Power pedaling rate relationships were constructed from the torque-pedaling rate relationships to form the expression: Power = $PR \times T \times \pi/30$.

Statistics

Dependent variables were first summarized using descriptive statistics, (mean ± SD, minimum and maximum error values). The differences between laboratory and field regression coefficients (maximum torque, slope) and calculated variables (maximum power, optimal pedaling rate) were then assessed using paired t-tests for dependent samples; alpha was set at 0.05. Moreover, individual power-pedaling rate curves constructed from laboratory trials allowed individual maximal power to be predicted for any pedaling rate. We compared individual subject measured power output and torque data from the field trials to laboratory derived predicted power (for the same field PR) using modified Bland-Altman plots (Altman and Bland 1983). Field power was used as the reference for all comparisons.

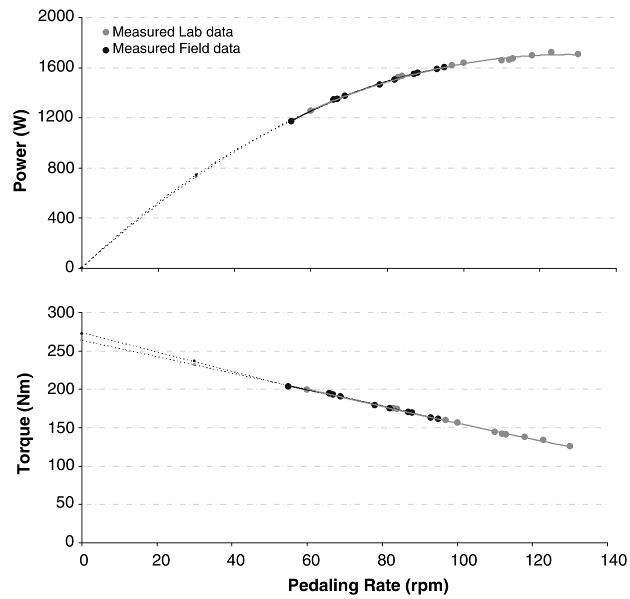

Fig. 1 Representative data from one representative cyclist depicting the measured range of torque-pedaling rate (*below*) and power-pedaling rate (*above*) relationships measured during laboratory and field trials. The *black data points* represent the field trials and the *gray data points* represent the laboratory trials. It can be observed that within 4 s, laboratory data were measured in the pedaling rate range of 60–130 rpm. Furthermore, it can be observed that within 7 s, field data were measured in the pedaling rate range of 55–95 rpm. The *dotted line* represents the forecast relationship from the y-intercept to the first measured data points

Results

Both laboratory and field torque-pedaling rate data showed good linear fit ($r^2 = 0.990 \pm 0.01$; 0.983 ± 0.02, respectively; Fig. 1). Mean ± SD data of the dependent variables for field and laboratory trials are shown in Table 1. Dependent variables were not significantly different between the laboratory and field trials; maximum torque ($P = 0.840$), maximum power ($P = 0.984$) and optimal pedaling rate ($P = 0.863$). However, individual variations can be observed in the percent difference data between laboratory and field.

Table 1 Individual values and percent difference from field values for all subjects ($n = 7$) derived from laboratory and field maximal torque-pedaling rate and power-pedaling rate relationships. Maximum torque represents the y-intercept of the torque-pedaling rate linear regression equation; maximum power and optimal pedaling rate represent the power and velocity components at the apex of the parabolic power-pedaling rate relationship. No significant differences were found between any laboratory or field variables ($P > 0.840$)

	Maximum torque (Nm)			Maximum power (W)			Optimal PR (rpm)		
	Laboratory	Field	Difference (%)	Laboratory	Field	Difference (%)	Laboratory	Field	Difference (%)
Subject 1	290	282	–3.0	1872	1845	–1.5	123	125	1.5
Subject 2	274	275	0.1	1782	1894	5.9	124	132	5.8
Subject 3	252	252	–0.1	1780	1696	–4.9	135	129	–4.8
Subject 4	251	262	4.5	1778	1776	–0.2	135	129	–4.9
Subject 5	264	273	3.2	1697	1626	–4.4	123	114	–7.8
Subject 6	291	271	–7.5	2092	2063	–1.4	137	145	5.7
Subject 7	242	245	1.0	1536	1644	6.5	121	128	5.6
Mean	266	266	–0.3	1791	1792	0.01	128	129	0.2
SD	20	13	4.0	169	156	4.6	7	9	5.9
Minimum	242	245	–7.5	1536	1626	–4.9	121	114	–7.8
Maximum	291	282	4.5	2092	2063	6.5	137	145	5.8

The average torque-pedaling rate (below) and power-pedaling rate (above) relationships for both laboratory and field data are presented in Fig. 2. Neither the slope (–1.040 ± 0.09, –1.035 ± 0.10; $P = 0.891$) nor the y-intercept (maximum torque; 266 ± 20, 266 ± 13; $P = 0.840$) of the regression equations significantly differed between the laboratory and field trials, respectively.

The variability of these data is presented in Fig. 3. The modified Bland Altman plots display the absolute torque, power and percent difference of predicted values (matched for pedaling rate from laboratory derived regression coefficients) from actual data measured in the field. Despite a low average error (0.1 ± 3.3 %; 0.09 ± 5.7 Nm; –0.4 ± 52.6 W), the plot shows individual variation (range: –6.2 to 6.1%). The 95% confidence interval for the mean of these difference scores was ± 0.7% (±10.8 W; ± 1.2 Nm).

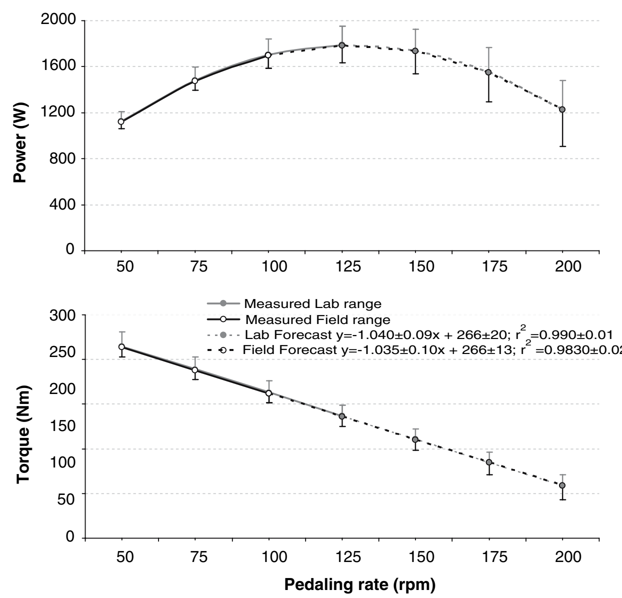

Fig. 2 Graph of mean (±SD) torque-pedaling rate regression equations and power-pedaling rate relationships for laboratory and field tests. The linear equations represent the average slope and y-intercepts for all participants ($n = 7$). The *solid lines* represent the measured range of data and the *dotted lines* show the forecast relationship. The average fit of all seven regression equations (r^2) is presented with the equations

Discussion

Our major findings were that mean torque- and power-pedaling rate relationships, maximum torque, maximum power and optimal pedaling rate values were nearly identical. Thus, when considering group data for our unique population, it appears valid to use laboratory and field measures interchangeably. This similarity suggests that velodrome performance can be accurately modeled using laboratory-based data. Moreover, this finding suggests that a variety of power and fatigue aspects can be carefully evaluated in a controlled laboratory setting and used to accurately model performance outcomes.

Our cyclists' data for maximum power, maximum torque and optimal pedaling rate compare well with previously reported data for athletes (Davies and Sandstrom 1989; Martin et al. 1997; Dorel et al. 2005). Of note is the similarity between our data and those recently published for elite French sprint cyclists by Dorel et al. (2005). The combination of our data with those collected by Dorel et al. (2005) provides a reference for the minimum fitness

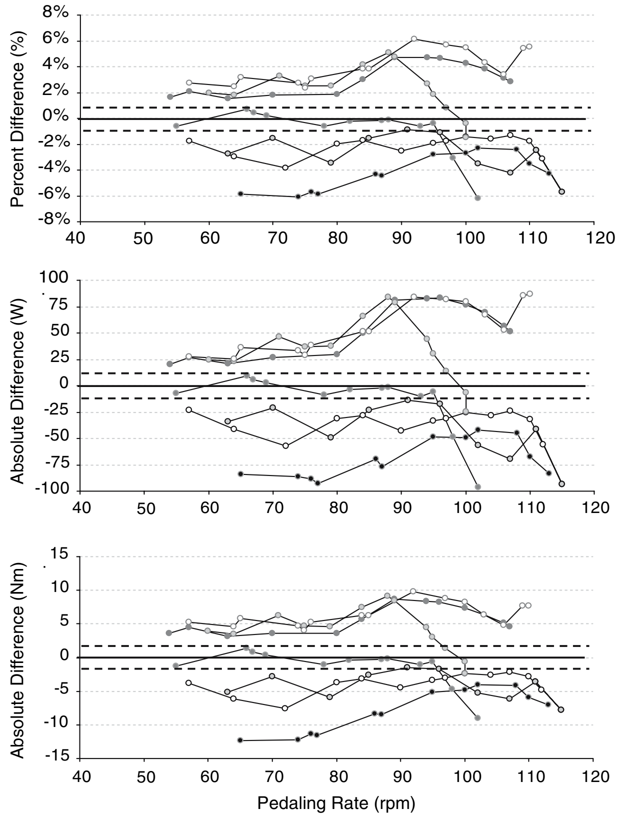

Fig. 3 Modified Bland-Altman plots of absolute torque (below), absolute power (middle) and error % of predicted power (matched for pedaling rate from laboratory-derived regression coefficients) from actual data measured in the field. The mean error % (±SD) for all participants (n = 7) was 0.1 ± 3.3 %. The *dotted lines* represent the 95% CI. The plot shows the individual variation between laboratory and field torque and power

requirements expected of international sprint cyclists. Dorel et al. (2005) presented maximum power data for 12 elite French sprint cyclists (83.6 ± 5.3 kg) of 1600 ± 116 W (19.3 ± 1.3 W kg^{-1}) during seated force–velocity tests. To our knowledge, data as impressive as these only exist in our (Gardner et al. 2005) recent description of the raw power demands during elite domestic and international match sprint finals and semifinals (1969 ± 239 W; 22.6 W kg^{-1}) and in the present study (1791 ± 169 W; 20.8 W kg^{-1}).

Optimal pedaling rate, which has been reported to closely relate to muscle fiber composition (Hautier et al. 1996) and represent a stable neuromuscular trait in trained cyclists (Martin et al. 2000) was reported by Dorel et al. (2005) to be 129.8 ± 4.7 rpm. Our data are consistent with those reported by Dorel et al. (2005) and show no significant difference between values for optimal pedaling rate measured in the laboratory and in the field (128 ± 7 rpm and 129 ± 9 rpm; P = 0.905, respectively). Furthermore, maximum torque, which may be representative of bicycle-specific leg strength (Driss et al. 2002) was slightly higher in the present study than previously reported values (Dorel et al. 2005). The slightly higher values for torque and power data may in part be due to the fact that cyclists were allowed to stand out of the saddle during our trials, which is known to facilitate greater power and force production (Reiser et al. 2002).

Our data do not agree well with those of Bertucci et al. (2005) who recently reported that field-based values of maximum torque, maximum power and maximum pedaling rate were significantly greater than those recorded using a bicycle mounted on a trainer. Those authors suggested that the inability of an ergometer to oscillate side to side during laboratory sprinting might be a major contributor to lower body power production. Although we do not know exactly why our data differ from those of Bertucci et al., we can speculate on two plausible explanations. First, the ''ergometer'' used in their study was, in fact, a trainer upon which a standard bicycle was mounted. The stability of such a trainer may be less than a typical ergometer and thus their ''ergometer'' data may have been compromised. Alternatively, the cyclists we tested in this study were elite track cyclists who are well trained at maximal power production. Thus, it could be that the ability to produce similar power during laboratory and field trials is a characteristic of elite level skill performance. Most likely, this question deservers further study.

Martin et al. (1997) previously used much smaller inertial loads and hence more rapid pedal acceleration (3–4 s) to determine maximum power across a broad range pedaling rates (80–171 rpm). In pilot testing, they found values for maximum power to be stable across a range of inertial loads (from 5.6 to 2.6 kg m^2). The present inertial loads of field data are approximately sevenfold higher (69.7 ± 3.8 kg m^2) than those previously reported. The use of large inertial loads poses two potential limitations. First, large inertial loads may induce fatigue; a longer duration will be required to accelerate across any specified range of pedaling rates and that extra time may allow fatigue to develop. In the present study, the torque-pedaling rate relationships were highly linear, $r^2 > 0.98$ for the field and laboratory trials, with no indication that the data were influenced towards the end of the trial by the large inertial load. Second, in order to avoid fatigue the apex of the parabolic power-pedaling rate relationship must be determined by extrapolation outside the measured data. Our mean data suggest that maximum power can be accurately predicted without actually reaching the pedaling rate required to elicit maximum power.

Although the mean group data in the present study were nearly identical, some individual variability between laboratory and field values was observed. A limitation of this study is that we are only able to speculate if this individual variability was caused as a result of our study conditions (i.e., laboratory vs. field tests) or by day-to-day physical and technical test error. This finding does not negate the use of laboratory tests to model field performance, but does emphasize the need for caution when inferring the predictive power of individual data derived from laboratory tests.

The present data show that the lowest amount of variability between the laboratory and the field trials existed for maximum torque, thus providing a stable anchor point (at low PR) to the torque-pedaling rate linear relationship. In contrast, more individual variation emerged in the slope of the same function. This may be due to a number of factors. First, individual motivation differences must always be considered when testing elite athletes. We suggest that competition derived data could provide a field-based solution to this issue and should be encouraged in scientific literature. Second, one might suggest that despite the good regression coefficients, fatigue was still present in the linear regression at higher pedaling rates on an individual basis. This observation might support the findings of Beelen and Sargeant (1991), who suggest that even in a very short-term exercise of 6 sec the muscle power may decrease as a consequence of selective fatigue in the faster most fatigue-sensitive muscle fibers. Thus, data in the present study might be slightly influenced by the magnitude of the inertial load. Third, it may be that these data were affected by limitations in the SRM powermeter (from a standing start) that often resulted in only a small number of sample points to construct the linear relationship for the laboratory data (n = 4–9). With the increased popularity of portable power devices for measuring torque and pedaling rate relationships (MacIntosh et al. 2004; Bertucci et al. 2005; Martin et al. 2006), future investigations might seek to understand the validity of function coefficients under conditions of different inertial load and test durations.

In summary, for elite sprint cyclists we found similar mean group torque-pedaling rate relationships during all-out brief exercise in the laboratory and in the field. Although some individual variability is noted in the present data, this finding suggests that field performance may be adequately modeled using laboratory-derived parameters. However, the data described in this study only represent the athlete's maximal capabilities of less than 7 s and therefore does not directly assess aspects of neuromuscular fatigue or pacing strategies. For a truly successful laboratory-derived modeling of field performance, future research should seek to understand the characteristics of more dynamic and sustained track sprint cycling events such as the 200 m and 1000 m time trials, which last up to and beyond 60 s.

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