Comparison of nine theoretical models for estimating the mechanical power output in cycling

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An appendix containing the equations can be found at <http://bjism.bmj.com/supplemental>

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Objective: To assess which of the equations used to estimate mechanical power output for a wide aerobic range of exercise intensities gives the closest value to that measured with the SRM training system.

Methods: Thirty four triathletes and endurance cyclists of both sexes (mean (SD) age 24 (5) years, height 176.3 (6.6) cm, weight 69.4 (7.6) kg and $\text{VO}_{2\text{MAX}}$ 61.5 (5.9) ml/kg/min) performed three incremental tests, one in the laboratory and two in the velodrome. The mean mechanical power output measured with the SRM training system in the velodrome tests corresponding to each stage of the tests was compared with the values theoretically estimated using the nine most referenced equations in literature (Whitt (*Ergonomics* 1971;14:419–24); Di Prampero *et al* (*J Appl Physiol* 1979;47:201–6); Whitt and Wilson (*Bicycling science*. Cambridge: MIT Press, 1982); Kyle (*Racing with the sun*. Philadelphia: Society of Automotive Engineers, 1991:43–50); Menard (First International Congress on Science and Cycling Skills, Malaga, 1992); Olds *et al* (*J Appl Physiol* 1995;78:1596–611; *J Appl Physiol* 1993;75:730–7); Broker (*USOC Sport Science and Technology Report* 1–24, 1994); Candau *et al* (*Med Sci Sports Exerc* 1999;31:1441–7)). This comparison was made using the mean squared error of prediction, the systematic error and the random error.

Results: The equations of Candau *et al*, Di Prampero *et al*, Olds *et al* (*J Appl Physiol* 1993;75:730–7) and Whitt gave a moderate mean squared error of prediction (12.7%, 21.6%, 13.2% and 16.5%, respectively) and a low random error (0.5%, 0.6%, 0.7% and 0.8%, respectively).

Conclusions: The equations of Candau *et al* and Di Prampero *et al* give the best estimate of mechanical power output when compared with measurements obtained with the SRM training system.

Traditionally, mechanical power output has been measured in endurance cycling modalities,^{1,2} and more recently in triathlon,³ in order to determine exercise intensity zones, to evaluate the physiological effects of training, and to quantify training and competition load. Until now, evaluation of mechanical power output has been carried out in the laboratory for two main reasons: (a) greater control can be maintained; (b) because sufficiently accurate technology did not exist to measure it in specific training and competition conditions. Thanks to technological developments in sport, new systems have been produced for measuring the mechanical power output generated by an athlete on his own competition bicycle (Polar, SRM, Power Tap and Powertec).^{4–5} Of these, the SRM training system (Schoberer Rad Messtechnik, Jülich, Germany) has become one of the most referenced systems in scientific literature for measuring mechanical power output in training and competition conditions.^{6–10}

Currently there are researchers, coaches and athletes who, for different reasons, are not disposed towards this technology. In this case, theoretical models are the only way to estimate mechanical power output in different situations. Various equations for estimating mechanical power output have been published; the most commonly used are those proposed by Whitt,¹¹ Di Prampero *et al*,¹² Whitt and Wilson,¹³ Kyle,¹⁴ Menard,¹⁵ Olds *et al*,^{16,17} Broker⁶ and Candau *et al*.¹⁸ These models all depend on different variables, the most important being the system displacement speed. Many of them also include other variables such as the athlete's morphology, terrain and environmental factors. Owing to the lack of a reference system that directly measures mechanical power output in cycling, these theoretical models have not been able to be validated. Now the SRM training system can be used as a reference system¹⁹ to assess the precision and accuracy of this type of equation.

The aim of this study was to assess which of the equations for estimating mechanical power output over a wide aerobic range of exercise intensities corresponds best to measurements obtained with the SRM training system in an incremental velodrome test to exhaustion.

METHODS

Subjects

Thirty four mountain bike and road cyclists and triathletes of both sexes participated in the study. Subjects with a heterogeneous performance level were selected, both national and international, to have as wide a range as possible of mechanical power output, as it was important to correctly define the performance of the different equations for extreme values also. Mean (SD) age, height, weight, peak power output (PPO) and maximal oxygen uptake ($\text{VO}_{2\text{MAX}}$) were 24 (5) years, 176.3 (6.6) cm, 69.4 (7.6) kg, 355 (41) W and 61.5 (5.9) ml/kg/min, respectively. Mean competitive experience was 4.5 (1.7) years. All experimental procedures were approved by the ethics committee of the High Performance Centre of Sant Cugat. All subjects gave written informed consent before testing, and the study was performed according to the Declaration of Helsinki.

Incremental laboratory test

About 3 or 4 weeks before the beginning of the velodrome tests, an incremental laboratory test was performed by each subject on a cycloergometer with electromagnetic brakes (CardiGis; G&G Inovación, La Bastida, Alava, Spain), with which all the subjects had been familiarised. After a 10 min warm-up at 100 W, the test began at an initial load of 130 W for the women

Abbreviations: MSEP, mean squared error of prediction; PPO, peak power output; RE, random error; SE, systematic error; $\text{VO}_{2\text{MAX}}$, maximal oxygen uptake

and 200 W for the men. Then, load was increased by 30 W every 4 min until $R \geq 1.00$. From then on, increases of 10 W/min were made until exhaustion. VO_2 and mechanical power output were measured in real time, breath by breath, during the whole test, using an indirect integrated calorimetry system (Quark PFT; Cosmed, Rome, Italy). The PPO was calculated using the equation proposed by Kuipers *et al.*²⁰ and $\text{VO}_{2\text{MAX}}$ was determined as the mean VO_2 value of the last 30 s effort, when at least two criteria recommended by the British Association of Sport and Exercise Sciences²¹ were fulfilled.

Experimental design

The experimental design consisted of two incremental velodrome tests. For 2 weeks before the tests, subjects familiarised themselves with the protocol by performing two incremental exercises, the first to $\sim 85\%$ PPO and the second to exhaustion. Once the familiarisation period had finished, the two incremental velodrome tests were performed. The tests were carried out on flat ground in order to obtain data corresponding to real training and competition conditions in the velodrome. The training and nutritional conditions under which the athletes performed the tests were controlled: an active recovery (2 h cycling at $\sim 50\%$ PPO) was programmed during the 48 h before each test, and a diet rich in carbohydrates ($\sim 75\%$) was ingested for the 3 days before each test. All the tests were performed at sea level.

Incremental velodrome test

The incremental velodrome test used in this study was that recently validated by González-Haro *et al.*²² All the subjects rode the same model of classical track bicycle (the tyres of which were inflated to 133.8 psi) and wore the same kind of clothes (short sleeved jersey, cycling shorts, clip shoes and slotted helmet). Ambient variables—temperature ($^{\circ}\text{C}$), humidity (%) and barometric pressure (mmHg)—were controlled and validated by the Fabra Observatory of Barcelona. Wind velocity was measured with a Speedwatch wind gauge (JDC Electronic SA, Yverdon-les-Bains, Switzerland). Mechanical power output, displacement speed and pedalling frequency were measured directly with the SRM training system.

Estimation of mechanical power output

The mean values of all the subjects' variables at each of the stages of the two velodrome tests were used to estimate mechanical power output at each stage using the equations mentioned above (further details can be found at <http://bjsm.bmj.com/supplemental>). The most important variables on which the estimations of mechanical power output are based are displacement speed, overall weight of the system, and the aerodynamic variables that determine the projected frontal area of the system and the body surface area. Other secondary variables are slope, friction coefficients, atmospheric pressure and temperature.

Table 1 Subject characteristics and laboratory measurements

Variable	Mean (SD)	Range
PPO (W)	355 (41)	280–430
PPO per BM (W/kg)	5.5 (0.5)	3.7–6.4
GE (%)	22.6 (1.7)	19.9–27.8
$\text{VO}_{2\text{MAX}}$ (ml/kg/min)	61.5 (5.9)	50.7–73.8
$\text{VO}_{2\text{MAX}}$ (l/min)	4.2 (0.5)	3.4–4.9

BM, body mass; GE, gross efficiency; PPO, peak power output; $\text{VO}_{2\text{MAX}}$, maximal oxygen uptake.

Figure 1 Comparison of estimations of mechanical power output using the different equations and the value measured with the SRM training system. Eq. 1, equation of Whitt¹¹; Eq. 2, equation of Di Prampero *et al.*¹²; Eq. 3, equation of Whitt and Wilson¹³; Eq. 4, equation of Kyle¹⁴; Eq. 5, equation of Menard¹⁵; Eq. 6, equation of Olds *et al.*¹⁷; Eq. 7, equation of Olds *et al.*¹⁶; Eq. 8, equation of Broker⁶; Eq. 9, equation of Candau *et al.*¹⁸

Statistical analysis

Descriptive statistics were generated for all variables. A pilot study showed that the minimum sample size required for the results to have the appropriate precision was 34 subjects. Estimates of mechanical power output by the different equations were compared with the value obtained with the SRM training system, calculating the mean squared error of prediction (MSEP) as a measure of total error, as well as the systematic error (SE) and the random error (RE).²³ The level of significance was established at $p < 0.05$ for all statistical tests carried out.

RESULTS

Table 1 presents the results of the incremental laboratory test.

Figure 1 shows the ranges of the mean mechanical power output for each stage of the tests, both measured by the SRM training system and estimated by the different equations.

The results show that the equations of Olds *et al.*¹⁶ and Whitt and Wilson¹³ have a smaller MSEP than the other equations. In both cases, almost all the MSEP was due to an RE. On the other hand, the equation with the smallest RE was that of Candau *et al.*¹⁸ followed by those of Di Prampero *et al.*¹² Olds *et al.*¹⁷ and Whitt.¹¹ Furthermore, these four equations showed a moderate SE. Finally, the remaining equations showed a considerably higher RE, especially those of Whitt and Wilson¹³ and Olds *et al.*¹⁶ (table 2).

DISCUSSION

This study aimed to analyse the differences between mechanical power output estimated by nine different equations and that measured by the SRM training system over the widest possible range. The values obtained in the laboratory test varied over a wide range: 280–430 W. Bearing in mind the characteristics of the laboratory test, this range of values indicates that the athletes were at widely varying performance levels, from amateur cyclists²⁴ and triathletes²⁵ to elite cyclists²⁶ and professional triathletes.³ Thus, as can be seen in fig 1, a wide range of values for the mechanical power output comparison was guaranteed, for both the measurements and the estimations.

Table 2 MSEP, SE and RE between mechanical power output estimated by the different equations and that measured by the SRM training system

Equation	Reference	MSEP (%)	SE (%)	RE (%)
1	Whitt ¹¹	16.5	15.7	0.8
2	Di Prampero <i>et al</i> ¹²	21.6	21.1	0.6
3	Whitt and Wilson ¹³	8.9	3.3	5.6
4	Kyle ¹⁴	44.6	42.7	1.8
5	Menard ¹⁵	33.3	32.2	1.1
6	Olds <i>et al</i> ¹⁷	13.2	12.6	0.7
7	Olds <i>et al</i> ¹⁶	8.4	0.0	8.4
8	Broker ⁶	39.0	37.2	1.8
9	Candau <i>et al</i> ¹⁸	12.7	12.2	0.5

MSEP, mean squared error of prediction; RE, random error; SE, systematic error.

The theoretical models assessed in this study are based on a series of physical and physiological assumptions. In most cases, the equations had not previously been evaluated against any reference measurement system, so it was difficult to compare the results obtained in this study with those of other authors. Broker⁶ compared his model with mechanical power output measured with the SRM training system at a single constant speed of 52.3 km/h, obtaining a mean error of -3.4 (8.1)%. Other authors have compared their models with performance expressed in time: Olds *et al*^{16, 17} observed a mean difference between the measured performance and the estimated performance of 1.3% and 3.87%, respectively. One of the novelties of the present study is that it compares the most important models in literature for estimating mechanical power output in cycling with the output measured by a reference system, assessing a very extensive range of each of the models.

Aerodynamic variables that could influence the determination of the projected frontal area of the system and body surface area (bicycle shape and subjects' clothing) were standardised and therefore controlled. The equations of Whitt and Wilson¹³ and Olds *et al*¹⁶ showed the lowest MSEP (8.9% and 8.4%, respectively), although almost all of the error was due to RE (5.6% and 8.4%, respectively). Other equations that showed low MSEP and SE were those of Candau *et al*,¹⁸ Olds *et al*,¹⁷ Whitt¹¹ and Di Prampero *et al*¹² (12.7–21.6% and 12.2–21.1%, respectively). Of the latter equations, those of Candau *et al*¹⁸ and Di

Prampero *et al*¹² had a lower RE (0.5% and 0.6%, respectively). In spite of the equations of Whitt and Wilson¹³ and Olds *et al*¹⁶ having a low MSEP, we considered that they are not the best for estimating power output, as the error was mainly random, which is a difficult type of error to correct. On the other hand, the equations of Candau *et al*,¹⁸ Olds *et al*,¹⁷ Whitt¹¹ and Di Prampero *et al*¹² had a moderate MSEP, which was almost entirely due to SE, an error that can easily be corrected. Furthermore, the RE was very low (1.7–1.9 W) for these equations. Finally, the most functional equations, because they contain fewer variables to measure, are those of Candau *et al*¹⁸ and Di Prampero *et al*.¹²

In conclusion, the equations proposed by Candau *et al*¹⁸ and Di Prampero *et al*¹² are the best for estimating mechanical power output over a wide aerobic range of exercise intensities when compared with measurements made with the SRM training system.

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Competing interests: None.

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What is already known on this topic

- Over the last three decades, several theoretical models for estimating mechanical power output in cycling have been published.
- However, none of them could be validated, because no system existed to measure mechanical power output in specific training and competition conditions.

What this study adds

- This study used the recently developed SRM training system to assess which of the proposed theoretical models give the best estimate of the mechanical power output of cyclists in field conditions over a wide range of aerobic intensities.

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COMMENTARY

The modelling in question is a useful tool for estimating important variables when we do not have equipment for direct

precise assessment. Indeed, quantification of external load in aerobic sports and its relationship to performance are cornerstones to training. This paper contributes to the body of knowledge in the field of modelling for cycling training because it analyses the precision of several traditional models that could be used in clinical or practical (training) contexts to assess peak power output, prescribe exercise, and design training programmes with the most accurate method and best rationale. On the other hand, these models must be used with caution because they do not fit the data perfectly and obviously a new statistical analysis is required to better determine the accuracy of estimates. Finally, some practical applications would be interesting.

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Nicola Maffulli is Professor of Trauma and Orthopaedic Surgery at Keele University School of Medicine. Originally a free style Olympic wrestler, his sporting endeavours have included middle distance running, judo and sambo wrestling. His main clinical interests lie in the management of lower limb sports injuries and in paediatric musculoskeletal sports medicine. Having suffered from many of the ailments that he treats, Professor Maffulli hardly performs an operation that he himself has not received!

His main research interests in the field of sports medicine are the histology and biology of overuse tendon injuries and the effects of intensive training in young and older athletes. A florid research programme is underway with international collaborators.

Figure 1 Nicola Maffulli.