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ORIGINAL ARTICLE

Original characteristics of a new cycle ergometer

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Abstract The aim of this study was to describe and validate a new cycling ergometer with original characteristics that allow the measurement of biomechanical variables with position and crank inertial load used by the cyclist in field condition. The braking pedalling force, that permitted the simulation of the resistance to the cyclist in the field, is performed with a brushless electric motor. The validity and the reproducibility of the power output measurements were compared with the widely accepted SRM powermeter. The results indicate that taking into account a systematic error, the measurements are valid compared with the SRM, and the reproducibility of the power output measurements is similar to the SRM. In conclusion, this ergometer is the only one that allows at the same time for (1) valid and reproducible power output measurements at submaximal intensity, (2) utilisation of the personal bicycle of the cyclist, and (3) simulation of the inertial characteristics of the road cycling.

Keywords Power output · Powermeter · Reproducibility · Crank inertial load · Cycling

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1 Introduction

The power output (PO) generated by cyclists is one major key to their performance in competition. Thus, this mechanical variable is measured by coaches, practitioners and researchers in order to test the physical fitness level of their athletes, patients or subjects. These measurements can be performed in a laboratory by using, for example, a classical cycling ergometer (e.g. Monark, Kingcycle, Velodyne, Axiom ergometer, indoortrainer SRM, Wattbike) or in the field by using a mobile powermeter (e.g. SRM, PowerTap, Ergomo). Many cycling powermeters such as those listed are used by coaches, practitioners or researchers. These powermeters do not all have the same quality of PO measurement (i.e. reproducibility, validity and sensitivity). Poor reliability in PO measurements in the physical tests of performance affects the accuracy of subsequent analyses. PO measurements with poor reliability are unsuitable for tracking changes in performance with time between trials, and lack precision for assessment of performance in a single trial [1].

In addition, a non-valid PO does not allow (1) optimisation of the training program, (2) a comparison with other tests, (3) an accurate analysis of the data, and (4) a prediction of performance using a cycling model. Recent studies [2, 3] that have focused on the quality of ergometers have suggested that the PowerTap (Cyclops, USA) could also be considered as a powermeter usable for scientific research, for high-level athletes during training or for test protocols. However, other powermeters such as the Polar mobile ergometer (S710, Kempele, Finland), the Ergomo device (G-Sensortrchnik GmbH und Co. KG, Mörfelden-Walldorf, Germany), the Lode (Excalibur Sport), the Kingcycle (EDS Portaprompt Ltd., High Wycombe, UK), the Axiom ergometer (Elite, Fontaniva, Italy), the Velodyne (Frontline Technology, Inc., Irvine, CA) and the Monark ergometer (Varberg, Sweden) should be used with precaution according to their different technical characteristics (Table 1). For evaluation of the effect of training or detraining with PO measurement, it is important to have an estimation of the variation due to the technical error of the powermeter [14]. Van Praagh et al. [21] suggested that the range of the technical error for PO recorded using ergometers should be within ±5%. For usage with high-level athletes, it may be considered that this technical error should be closer to ±2%.

Biomechanical factors can influence physiological responses, perception of the exercise and efficiency of an individual riding a bicycle ergometer at a given PO [22]. One of the most important factors is the inertial characteristics of the ergometer that can alter (1) the crank kinematics (e.g. cadence variability) [23, 24], (2) the tangential crank force [24], (3) the crank torque [24, 25],

Table 1 Comparisons of the validity and reproducibility of the power output measurements of ergometers frequently used by cycling researchers or coaches

Ergometers	Validity	Reproducibility	Usable with a race bicycle
SRM Crank powermeter [2–4]	*Yes*, tested from dynamic calibration and Monark ergometer. Considered as the gold standard of the powermeter	*Yes*, CV from 0.7 to 2.1%	*Yes*, but *No* for the SRM performance ergometer
PowerTap [2, 3]	*Yes*, validated from dynamic calibration and the SRM	*Yes*, CV from 0.9 to 2.9%	*Yes*
Polar S710 [5–7]	*No*, comparison from the SRM. From −23 to +7% of the SRM PO	*No*, the median of random error was 51%	*Yes*
Ergomo [8, 9]	*No*, comparison from SRM, PowerTap and Monark. Can be altered by the asymmetry of the pedalling observed [10] on the cyclist. From −3 to +12% of the SRM PO	*No*, CV close to 4% Random error altered by the pedalling asymmetries	*Yes*
Axiom ergometer [11]	*No*, comparison from SRM, from +5 to 12% of the SRM PO. Drift of the measurements with the time	*Yes*, CV of 2.2%	*Yes*
Lode (Excalibur Sport) [12, 13]	No mechanical validation, just tested from the comparison of the physiological data (oxygen consumption). No difference was found from 100 to 300 W	Not mechanically tested, just tested from the comparison of the physiological data. It seems correct	*No*
Cyclus 2 [13]	No mechanical validation, just tested from the comparison of the physiological data (oxygen consumption). No difference was found from 100 to 300 W	Not mechanically tested	*Yes*
Kingcycle [14–16]	*No*, +10% of the SRM PO. Validity altered by the change in weight distribution on the saddle and ambient temperature, humidity, or barometric pressure	Appears less reproducible than the SRM	*Yes*
Velodyne [17]	No mechanical validation, just tested from the comparison of the physiological data (oxygen consumption) on a Monark. No difference was found to 350 W	Not tested	*Yes*
Monark ergometer [4, 18, 19]	*No*, comparison from dynamic calibration. Underestimation from −4.5 to −8%. Higher PO when increasing (0–353 W) than decreasing (353–0 W) the exercise intensity. The validity can be affected by a hysteresis phenomenon and by an alteration of the belt force friction due to a varying of the belt temperature. The newest Monark are more accurate (117–294 W) than the oldest. However, good agreement between the Monark and SRM PO values has been reported [4, 20]	Not tested. Can be altered by the same things that alter the validity	*No*

(4) the preferred pedalling cadence [26], (5) the load pulse sum [27], (6) the gross efficiency [26], and (7) the rating of perceived exertion [22, 25]. If ergometers with different inertia of flywheels are used for measurements, the results of experiments cannot be compared with good validity [27]. Very often, ergometers have different flywheel inertial characteristics involving crank inertial load (CIL) values significantly lower than the road cycling conditions. That is one of the reasons why most of the ergometers have flywheels with a low inertia, or flywheels with a low rotational velocity. The characteristics of different ergometers used frequently in cycling research or by the coaches of elite athletes are shown in Tables 2 and 3. These data indicate that the new ergometers offering a range of CIL and pedalling cadences (from 10 to 50 km h^{-1}) closer to those observed on the road would be beneficial. The Velodyne, the SRM ergometer and the Kingcycle can also simulate the CIL but not all of the corresponding pedalling cadences. However, the validity of the Velodyne has not been scientifically demonstrated and the Kingcycle has not had its validity compared with the SRM [14, 15]. The SRM ergometer uses a system of gears combined to a flywheel that allows a large variation of CIL. However, with the SRM ergometer the cyclist cannot use their personal bicycle. The Axiom ergometer can be used to allow a simulation of uphill conditions (10–20 km h^{-1}). However, the simulation of the flat condition at 50 km h^{-1} appears to be compromised. The Cyclus 2 and the Monark ergometers appear limited concerning CIL and KE simulation. The gear ratios and inertia of flywheels for these ergometers seem too low. To simulate uphill conditions in races it is fundamental to simulate a low pedalling cadence close to 70 rpm observed in uphill field conditions [e.g. 28] and close to 110 rpm on the flat up to 130 rpm during maximal sprints.

In order to optimise the quality of fitness assessment tests, it is important to use an ergometer which allows (1) control of the inertial characteristics in order to simulate the actual cycling conditions (i.e. to obtain the same CIL for flat and uphill road cycling), (2) valid, reproducible and sensitive PO measurements, and (3) the use of the cyclist's own bicycle to maintain the cyclist's usual riding position.

Table 2 Ranges of possible CIL for different ergometers with a gear ratio from 39/32 to 53/11 (except for the Monark)

	CIL (kg m^2)
Race bicycle on the road	15.6–242.9
New ergometer	37–233.3
Axiom	6–92.6
Kingcycle	9–140.7
Velodyne	10–155.7
Cyclus 2	1.5–23.3
Bicycle on rollers	0.6–17.7
Monark (52/14)	5.2

With a total mass of cyclist and bike of 80 kg for the road condition

The aim of this study is to present a new ergometer that allows: (1) valid and reproducible PO measurements at submaximal intensity levels (100–300 W), (2) a CIL and kinetic energy similar to field cycling conditions, and (3) the use of the cyclist's own bicycle.

2 Methods

2.1 Design of the new cyclo-ergometer

2.1.1 Frame characteristics

The ergometer frame (Figs. 1, 2) was built from modular structures formed by aluminium profiles (Norcan, France, 0.08 × 0.08 or 0.06 × 0.08 m) connected by standard M8 screws. The profiles were assembled with corner triangles (0.087 × 0.085 or 0.087 × 0.04 m, elastic limit 220 N mm^{-2} and maximal stress 260 N mm^{-2}).

2.1.2 Working, braking and PO measurement

The personal bicycle of the cyclist is fitted on the ergometer (Fig. 2). When the cyclist pedals, the kinematic chain (Fig. 3) is started. From the transmission chain and double chevron gears the inertial flywheel is activated at the desired rotational velocity. By using the electric motor at its nominal rotor velocity and by storing the desired kinetic energy, different gears were connected to a bicycle freewheel fixed on the flywheel inertia. The possibility to alter the inertial flywheel rotational velocity allows the generation of inertial values similar to road cycling. The speed ratio modification between the crank arm of the bicycle and the ergometer allows for a crank inertial load from 37 to 233 kg m^2 to be generated. The inertial flywheel cannot be motorised, because if the flywheel rotational velocity is higher than the cyclist's pedalling cadence, the freewheel is triggered.

The pedalling resistive force is provided by using a brushless electric motor (Panasonic, 2.5 kW). The maximal torque from the rotor and the maximal rotational velocity are 7.94 N m and 3,000 rpm, respectively. A brushless motor was chosen because it offers several advantages over an asynchronous motor, including more torque per mass; higher efficiency and reliability; reduced noise; and longer lifetime. The motor is connected to the kinematic chain with a freewheel. This is connected by a tooth belt at two toothwheels (160 × 60 teeth) connected by the double universal joint at the inertial flywheel (Figs. 1, 3). The freewheel is

Table 3 Pedalling cadences range on actual conditions (10–50 km h^{-1}) and on different ergometers respecting the simulation of the kinetic energy

Cyclist speed (km h^{-1}):	10	20	30	40	50
Kinetic energy (J):	309	1,235	2,778	4,938	7,716
Range of pedalling cadence (rpm) for a race bicycle gear ratios (53/11 to 39/32) on the field	17–68	34–135	51–203	71–270	89–338
Range of pedalling cadence (rpm) for a mountain bike gear ratios (44/11 to 32/34) on the field	21–88	41–175	62–263	82–350	103–438
Pedalling cadence possible for the new ergometer	17–87	34–142	51–213	68–285	85–356
Minimal pedalling cadence on SRM ergometer (rpm)	54	59	66	77	91
Minimal pedalling cadence on Monark (rpm)	85	169	254	338	423
Axiom pedalling cadence (rpm) with 53/11 and 39/32	26–104	53–207	79–311	105–415	132–519
Velodyne pedalling cadence (rpm) with 53/11 to 39/32	20–78	40–156	59–234	78–312	99–391
Cyclus 2 pedalling cadence (rpm) with 53/11 to 39/32	58–229	116–458	174–688	231–917	290–1,146
Kingcycle pedalling cadence (rpm) with 53/11 to 39/32	21–82	41–163	62–245	83–326	103–408

The KE was calculated with a mass of cyclist and bike of 80 kg

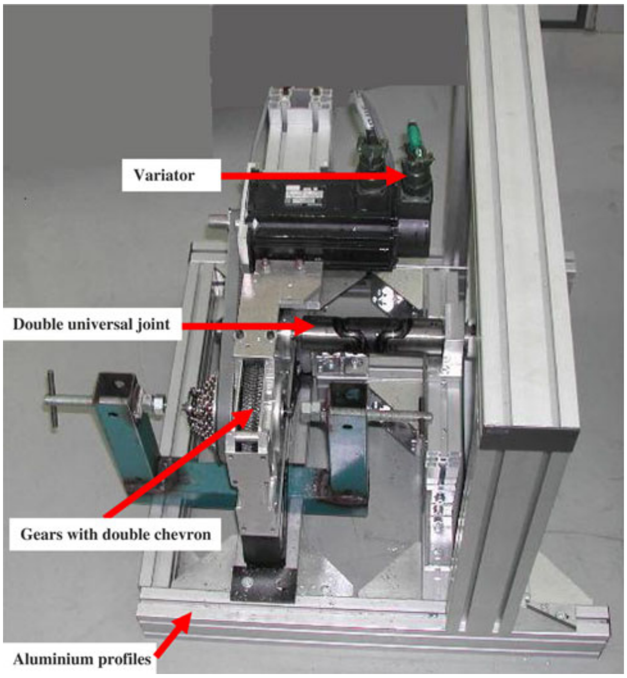

Fig. 1 Image of the new ergometer

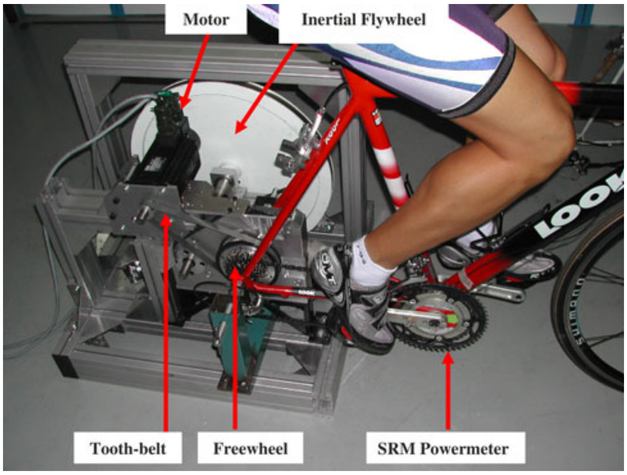

Fig. 2 The new ergometer equipped with a race bicycle fitted with a SRM powermeter during the validation protocol

equipped with 10 sprockets with 11–34 teeth. When one wants to reproduce downhill conditions, the motor drives the inertial flywheel. However, when one wants to reproduce the aerodynamic and gravitational resistance forces of road cycling, the motor is used to generate a resistive torque by using the motor as a dynamo. To control and modify the resistive torque, a rheostat is connected to the motor (Fig. 4). By connecting the variator to a computer, the electric motor (60 Hz) can measure the torque (Nm) and the rotor velocity (rpm). From the torque (Nm) and rotor velocity (rad s^{-1}) it is possible to calculate the PO. The range of the PO measurements is between 20 and 2,500 W.

2.1.3 Kinetic energy simulation

In order to obtain similar pedalling conditions between the ergometer and actual field cycling, an inertia flywheel (22 kg similar to that of the 818E Monark ergometer) was fixed on the ergometer frame to simulate the kinetic energy generated by a cyclist during field cycling conditions.

The rotational kinetic energy and the CIL were calculated in order to simulate different conditions met in the field for cycling at speed between 10 and 50 km h^{-1} (Table 3). The CIL varies with the gear ratio (m) and the mass (kg) of the cyclist [20, 26, 29, 30] which corresponds to the inertia for each crank cycle. The CIL values for road

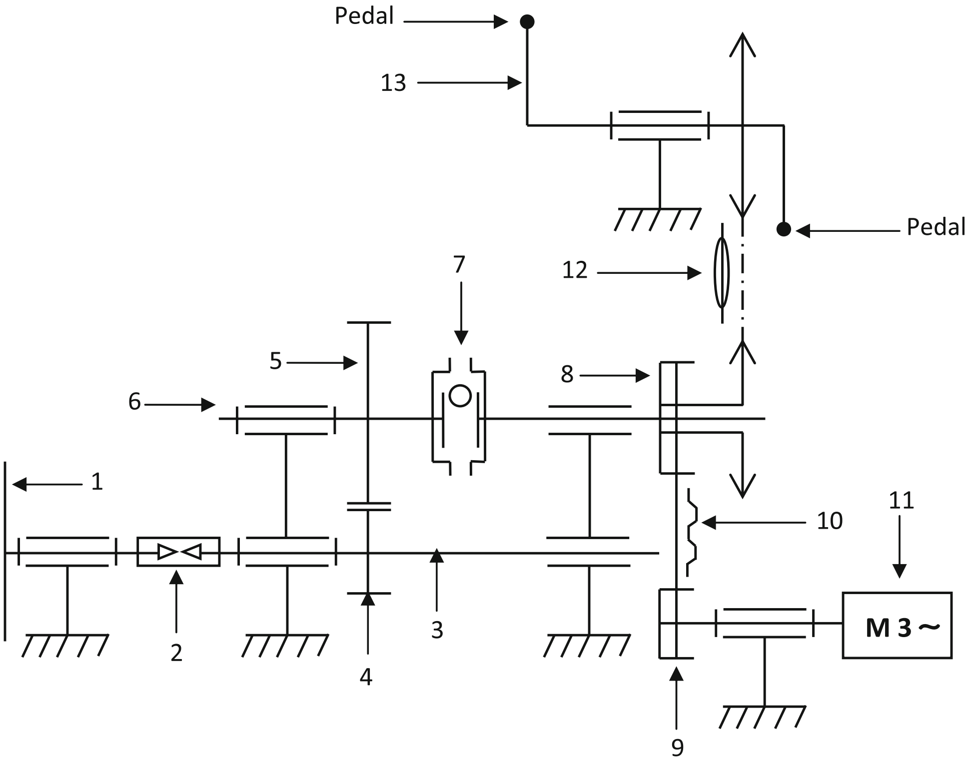

Fig. 3 Diagram of the kinematic chain. References of the components and inertia: *1*, inertial flywheel (0.746 kg m^2); *2*, double universal joint (0.00614 kg m^2); *3*, tooth-wheel of 60 teeth (0.00056 kg m^2); *4*, axle of the tooth-wheel of 60 teeth (0.00211 kg m^2); *5*, tooth-wheel of 160 teeth (0.03286 kg m^2); *6*, axle of the tooth-wheel of 160 teeth (0.00056 kg m^2); *7*, freewheel (0.0003 kg m^2); *8*, pulley of 80 teeth (0.00128 kg m^2); *9*, pulley of 20 teeth (0.000004 kg m^2); *10*, tooth-belt; *11*, motor; *12*, chain of the bicycle; *13*, crank arm of the bicycle

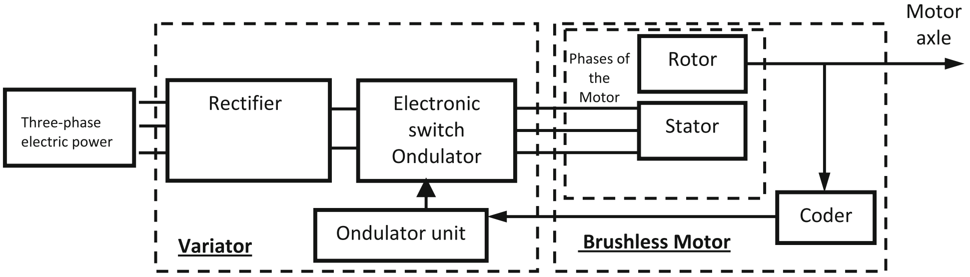

Fig. 4 Technical description of the braking system

cycling were calculated according to the studies of Hansen et al. [26, 30]:

$$\mathrm{CIL}\left(\mathrm{kg\,m}^2\right) = I_{\mathrm{P}} + (R_{\mathrm{F}}/R_{\mathrm{G}})^2 \left[R_{\mathrm{D}}^2(m_{\mathrm{B}} + m_{\mathrm{C}} + 2m_{\mathrm{D}} + m_{\mathrm{F}} + m_{\mathrm{G}} + m_{\mathrm{W}}) + (2I_{\mathrm{D}} + I_{\mathrm{G}})\right]$$

Where I_{D} is the rotational inertia of each wheel about its axis of rotation, 0.1786 (kg m^2); I_{P} the combined rotational inertia of the pedals, crank arms, and chain wheels about the crank axis, 0.0355 (kg m^2) and combined inertia of the double universal joint, gears (0.0134 kg m^2); I_{G} the rotational inertia of the freewheel, 0.0003 (kg m^2); m_{B} the mass of the bicycle frame, 6.416 (kg) (without the wheels, crank arms, and pedals); m_{C} the mass of the subject (kg); m_{D} the mass of each wheel, 1.973 (kg); m_{F} the combined mass of the chain wheels, crank arms, and pedals, 1.660 (kg); m_{G} the mass of the freewheel, 0.320 (kg); m_{W} the mass on the weight magazine (kg); R_{D} the radius of each wheel, 0.3429 for the race bicycle and 0.3302 for the mountain bike (m); R_{F} the number of teeth in the chain wheel; R_{G} the number of teeth in the freewheel; V the linear velocity (km h^{-1}).

The CIL values for the ergometers were calculated according to the study of Edwards et al. [23].

CIL = I_{F} (gear ratio between the chain wheel and the freewheel × gear ratio between the freewheel and the flywheel)^2, thus:

$$\mathrm{CIL} = (I_{\mathrm{G}} + I_{\mathrm{D}})(R_{\mathrm{F}}/R_{\mathrm{G}})^2 + I_{\mathrm{F}}(R_{\mathrm{F}}/R_{\mathrm{G}} \times 160/60)^2 + I_{\mathrm{P}}$$

Where I_{F} is the inertia of the ergometer flywheel (kg m^2).

The kinetic energy (KE) values of road cycling were calculated according to the following equation: KE (J) = $1/2 \times (m_{\mathrm{B}} + m_{\mathrm{C}} + 2m_{\mathrm{D}} + m_{\mathrm{F}} + m_{\mathrm{G}} + m_{\mathrm{W}}) \times V^2 + 1/2 \times (I_{\mathrm{D}}) \times \omega_{\mathrm{D}}^2$.

Where ω_{D} is the rotational velocity of the wheels (rad s^{-1}), and V is the linear velocity (m s^{-1}).

The rotational KE values of the ergometer were calculated according to the following equation: KE (J) = $1/2 \times (I) \times \omega^2$, where I is the inertia value (kg m^2), and ω is the angular velocity of the flywheel (rad s^{-1}). The KE generated by the other ergometer elements in rotation according to their inertia and rotational velocity was taken into account, but this is negligible compared with the flywheel KE values.

2.2 Validation method of the new cyclo-ergometer

Before the first measurements with the ergometer, a running in process was performed for 24 h at a motor rotation speed of 800 rpm.

At first, after warming up of the ergometer (15 min at 800 rpm) the PO measurements were performed 15 times (for 25 s each) by the electric motor (60 Hz) with the bicycle connected to the ergometer at thirteen motor rotation velocities from 400 to 1,800 rpm (15 × 13 measurements at the same motor rotation speed) (Fig. 5). The data were averaged for each rotation velocity. This procedure was performed (1) to estimate the PO dissipated in the mechanical friction of the different ergometer and bicycle components in rotation; (2) to give an indication of the residual torque of the ergometer; and (3) to calculate the PO generated by the cyclist as follows: cyclist PO (W) = PO of the motor braking + PO due to the ergometer and bicycling mechanical friction.

Then, the validation procedure of the new cyclo-ergometer was performed using the SRM powermeter as a reference for the PO measurement. The SRM powermeter is composed of 20 strain gauges that measure the propulsive torque on the crank axle. The SRM powermeter also measures the crank rotational velocity. From the propulsive torque and the rotational velocity (10 Hz) the PO was computed. The scientific literature shows that this device produces valid and reliable PO measurements [3–6]. Before the study, the SRM was calibrated according to the manufacturer's recommendations (offset and slope of powermeter).

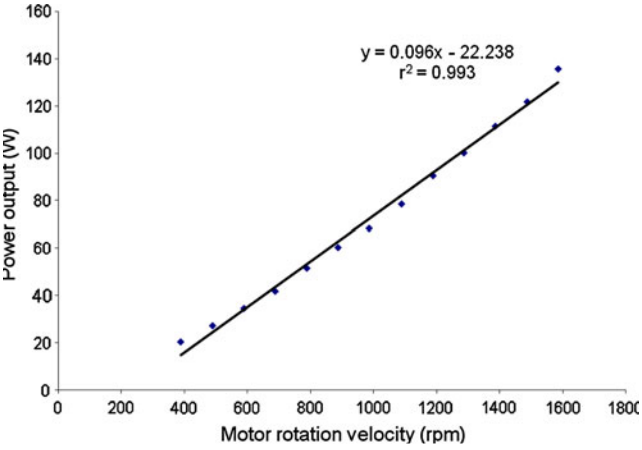

Fig. 5 Motor power output at different motor rotation velocities connected with a bicycle without cyclist

After a warming up on the ergometer (15 min at 800 rpm), competitive cyclist (22 years, 1.77 m, 70 kg) with his personal bicycle fitted with the SRM system performed the following protocol: 15 exercises (for 1 min each) with a pedalling cadence of 90 rpm in randomised order at 100, 200 and 300 W. At a pedalling cadence of 90 rpm the motor was used at his nominal rotational velocity of 800 rpm. The rest between each pedalling session was 15 s. The repetition of the trials (15 × 13 measurements at the same motor rotation speed) allows the reproducibility of the measurements to be analysed and the variation of the results to be tested in each condition. The subject was informed of all testing procedures, protocols, risks, benefits and time commitment before participating and voluntarily provided informed, written consent. The study was approved by the local institutional ethics committee (University of Franche-Comte).

2.3 Statistical analysis

The data of the tests with the cyclist at 100, 200 and 300 W were tested of heteroscedasticity by calculating the heteroscedasticity correlation between (1) the absolute differences between the ergometer PO (PO_{ERGO}) and the SRM PO (PO_{SRM}) and (2) the mean PO as described by Atkinson and Nevill [31]. Although this analysis showed that homoscedasticity was not present (Fig. 6), the data were logarithmically transformed according to the recommendations of Nevill [32] and Nevill and Atkinson [33]. The 95% levels of agreement of the PO differences between the SRM and the ergometer were defined using the method of Bland and Altman [34]. This statistical methodology is usually performed to compare and analyse the validity of new devices compared with a scientific reference device. The PO differences were drawn in relation to the mean values and 95% of the differences were expected to lie between the two "limits of agreement" which were mean difference ±1.96 standard deviation (SD) of the differences, expressed as bias ± random error according to Atkinson and Nevill [31]. 95% confidence interval (95% CI) for the bias was also calculated.

The coefficient of variation (CV) of data collected from the 15 measurements for each rotation velocity, from 400 to 1,800 rpm, without bicycle connection was calculated to assess the reproducibility and the sensitivity of the ergometer. To establish the reproducibility, the CV for PO_{SRM} and PO_{ERGO} was determined. CV was calculated as the standard deviation to mean ratio, multiplied by 100.

To complete these analyses a paired *t* test comparison was performed between the PO_{ERGO} and the PO_{SRM} measurements. A Bravais–Pearson correlation coefficient was calculated to determine the significance of the relationships

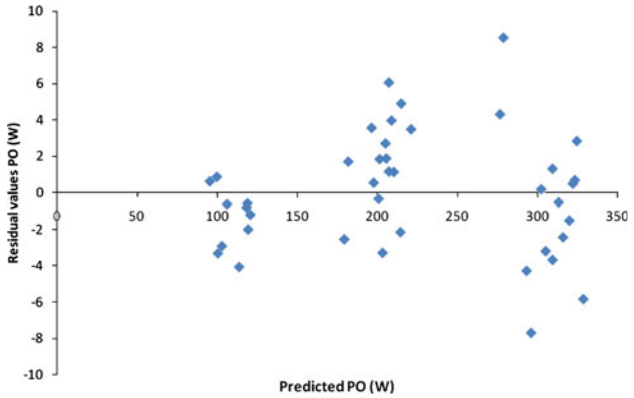

Fig. 6 Plot of predicted PO values against their residuals for the PO_{SRM} and PO_{ERGO} taking into account the systematic error of the new ergometer

between the two devices. The level of significance was set at $p < 0.05$. Data are presented as mean values ± SD.

3 Results

During the validation procedure, the motor velocity was 792 ± 0.2 rpm. The PO/motor velocity was determined (Fig. 5):

$$PO = 0.096\omega - 22.238\left(R^2 = 0.99\right)$$

where ω is the motor rotation velocity (with the bicycle mounted on the ergometer, but without cyclist). The PO generated by the residual torque of the ergometer with the bicycle without cyclist at 792 rpm was 53.8 W. This PO value had to be added to the PO of the motor measurements in order to compare with the SRM powermeter. For the measurements from 100 to 300 W, the 95% limits of agreement were 0.108 ± 0.068. The ratio limits of agreement of the PO differences between the two systems were 1.114 × ÷ 1.070 (95% CI = 1.041–1.192). The mean bias between PO_{SRM} and PO_{ERGO} was 20.1 ± 4.1 W. There was a significant difference between the PO_{SRM} and PO_{ERGO} value for a mean PO during the range of exercises from 100 to 300 W (218.8 ± 78.9 vs. 198.7 ± 76.5 W, respectively).

The mean CV for the PO measurement of the new ergometer is 1.4 ± 0.5%. According to the low CV value, the mean bias between PO_{SRM} and PO_{ERGO} can be considered as a reliable systematic error. When the PO of the new ergometer was corrected with the systematic error (+20.1 W), the absolute value of the bias between the PO_{SRM} and PO_{ERGO} was 2.6 ± 2 W (PO_{ERGO} = motor PO measurement + PO due to the residual torque + systematic error). Figure 6 shows the residual values of PO for the PO_{SRM} and PO_{ERGO} when taking into account the systematic error of the new ergometer (with the motor at 800 rpm and the pedalling cadence at 90 rpm). That shows the residual values increase in absolute value when the PO increases and that homoscedasticity was not present. This figure shows the residual values between the PO of the ergometer and the estimated function value elaborated between the PO of SRM and ergometer. In this condition, for the measurements from 100 to 300 W, the 95% limits of agreement were −0.006 ± 0.004 and the ratio limits of agreement were 1.006 × ÷ 1.004 (95% CI = 1.002–1.014). There was no statistical difference between the mean PO_{SRM} and the corrected mean PO_{ERGO} between 100 and 300 W (218.8 ± 78.9 vs. 218.8 ± 76.5 W, respectively).

4 Discussion

The most important finding of this study is that the new ergometer allows valid and reliable PO measurements at submaximal intensities between 100 and 300 W compared with the gold standard scientific SRM powermeter. The low value of CV (1.4 ± 0.5%) indicates that the PO_{ERGO} is reliable. This CV was similar (2%) to the SRM powermeter [6, 8]. The reliability of the measurement is one of the major qualities of an ergometer. Indeed, for high-level athletes a 1% variation of PO can constitute an important difference in the race results. In addition, the reliability is fundamental in order to track relatively small effects generated, for example, by a training program.

To obtain a valid measurement with this new ergometer, it is necessary to take into account a reproducible systematic error (20.1 ± 4.1 W). Taking this into account, the new ergometer demonstrates very good validity compared with the SRM powermeter (Fig. 7). Indeed, the ratio limits of agreement of the bias were 1.006 × ÷ 1.004 (95% CI = 1.002–1.014). A value of ratio of limits agreement of 1 indicates that the agreement between the two devices is perfect. Also, there is no statistical difference between the mean PO_{SRM} and PO_{ERGO} for the range PO of 100–300 W (Fig. 8).

In this study, a brushless motor was used at a nominal rotational velocity (800 rpm). Figure 5 shows the relationship between the new ergometer connected with a bicycle without cyclist and the SRM powermeter PO measurements at different rotational velocities (400–1,600 rpm). This PO value indicates the PO loss by the ergometer and the bicycle due to mechanical friction (20–120 W). Moreover, these results show a strong relationship between the two devices ($r = 0.99$). However, this figure shows a slight drift for the minimal and maximal values (400 and 1,600 rpm, respectively). These results suggest that it is important to use the ergometer at the nominal motor rotational velocity.

These results show that the new ergometer can generate valid and reproducible PO measurements compared with

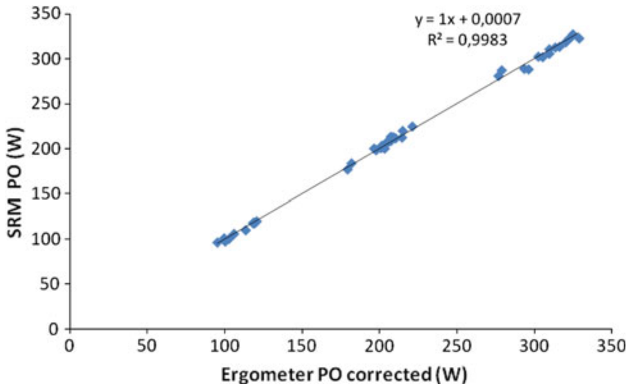

Fig. 7 Relationship between the power output of the SRM powermeter and the new ergometer taking into account the systematic error (PO corrected)

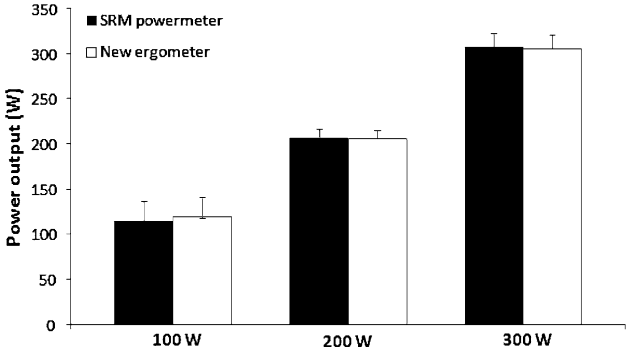

Fig. 8 Power output given by the new ergometer and the SRM powermeter from 100 to 300 W. No significant difference was observed

the SRM, which is considered as the gold standard powermeter [4]. Few of the current ergometers have been successfully compared with a dynamical calibration rig or with the scientific SRM powermeter. This new ergometer could be used for cycling PO measurements in scientific researches and for the physical testing of high-level cyclists.

The results of this study indicate that the new ergometer can generate CIL values close to actual field cycling (37–233 vs. 16–243 kg m^2, respectively, Table 2). In addition, the new ergometer can simulate the KE of road cycling for speeds between 10 and 50 km h^{-1} with the pedalling cadences used by the cyclist on his race bicycle (Table 3). To perform a field cycling simulation in the laboratory the ergometers must store on the flywheel the KE and CIL values obtained in road cycling. Indeed, several authors [24–26, 30, 35] have shown that the crank torque profile could be affected by a change in CIL or KE. Hansen et al. [26] have shown that the preferred pedalling cadence and the gross efficiency were affected by a modification of CIL (or KE). Bertucci et al. [25] indicated that a variation of CIL (and thus KE) between laboratory and road cycling could in part explain the higher perceived exertion in the laboratory condition. At this time this ergometer is the only one of all types of ergometers with PO measurements scientifically validated that reproduce the range of CIL that is obtained in actual field uphill, flat and downhill cycling conditions.

In the future it could be interesting to improve this ergometer by (1) adding the possibility for the cyclist to perform lateral oscillations with their bicycle, (2) improving the compatibility with different types of bicycles, such as a BMX bike (new Olympic discipline), and (3) reducing the mass of the ergometer to facilitate the transport.

5 Conclusion

In conclusion, the results suggest that the new ergometer allows: (1) valid and reliable PO measurements at submaximal exercise intensities compared with the SRM powermeter, (2) a good simulation of the CIL and KE at pedalling cadences used by cyclists during real road conditions (uphill and level ground), and (3) the utilisation of the cyclist's personal bicycle, which allows the usual position of the cyclist. To the best of our knowledge, it is the only ergometer that contains all these specificities.

In the future, it will be of interest that this new ergometer allows for lateral sways with the fixed bicycle to better simulate the real road cycling conditions, which will contribute to an improvement of the validity of the cycling field simulation in the laboratory.

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Conflict of interest The authors declare that they have no conflict of interest.

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