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Development and Evaluation of a New Bicycle Instrument for Measurements of Pedal Forces and Power Output in Cycling

Abstract

Determination of pedal forces is a prerequisite to analyse cycling performance capability from a biomechanical point of view. Comparing existing pedal force measurement systems, there are methodological or practical limitations regarding the requirements of scientific sports performance research and enhancement. Therefore, the aim of this study was to develop and to validate a new bicycle instrument that enables pedal forces as well as power output measurements with a free choice of pedal system. The instrument (Powertec[®]-System) is based on force transducer devices, using the Hall-Effect and being mounted between the crank and the pedal. Validation of the method was evaluated by determining the accuracy, the cross talk effect, the influence of lateral forces, the reproducibility and, finally, a possible drift under static conditions. Dynamic tests were conducted to vali-

date the power output measurement in reference to the SRM-System. The mean error of the present system was $-0.87 \pm 4.09\%$ and $-1.86 \pm 6.61\%$ for, respectively, the tangential and radial direction. Cross talk, lateral force influence, reproducibility and drift mean values were $< \pm 7\%$, $\leq 2.4\%$, $< 0.8\%$ and $0.02 \text{ N} \cdot \text{min}^{-1}$, respectively. In dynamic conditions, the power output measurement error could be kept below 2.35%. In conclusion, this method offers the possibility for both valid pedal forces and power output measurements. Moreover, the instrument allows measurements with every pedal system. This method has an interesting potential for biomechanical analyses in cycling research and performance enhancement.

Key words

Cycling · pedal forces · workload · ergometer

Introduction

In cycling, the transfer of metabolic energy into physical power or velocity of the rider-bike-system is not one-to-one. Environmental as well as mechanical and biomechanical factors affect cycling performance [8,25]. The propulsion of the bike is generated by pedal forces. Therefore, the determination of pedal forces is a major prerequisite to analyse cycling performance capability from a biomechanical point of view. The question is not why to measure pedal forces but how to do it. Comparing the different

existing instruments whose purpose is the determination of mechanical parameters concerning cycling propulsion, there are still methodological or practical limitations regarding the requirements of scientific sports performance research and enhancement.

The first studies conducting pedal force measurements were restricted to just one dimension, using either strain gauges fixed on the crank [13,22] or directly under the pedal to determine the normal force [5,10]. The next two generations of pedal forces

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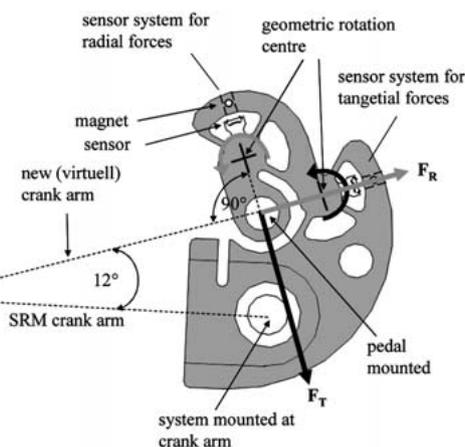
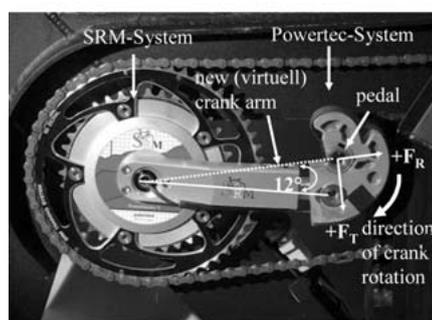


Fig. 1 2D pedal force measurement system (Powertec[®]) fixed at the end of the SRM-crank (left picture). Schematic of the mechanical construction of the Powertec[®]-System (right picture). Black and grey linear arrows: positive direction of tangential and radial force components; black and grey curved arrows: positive rotation direction of sensor sensitivity.

measuring instruments were able to measure two [1,9,16,17,19,23] and three dimensions [3,11,24], using strain gauges or piezoelectric elements [4,6] implemented in the pedal. However, most of these studies have been carried out in laboratory conditions. Even when investigations were conducted with bicycles on rollers or a motorized treadmill [24] instead of stationary cycle-ergometer, real outside cycling conditions could not be obtained. With high effort, most of these systems could be converted to on-road systems but few studies realized that [1,19]. Moreover, further calculations are necessary to obtain power output from the measured pedal forces and the angular velocity of the crank.

A more practical but very important disadvantage of the reported pedal force measuring systems is the fact that the shoe clip is restricted to the pedal system the device is built on. Cyclists would have to change their pedal-shoe interface, which means to readjust the foot position on the pedal, if they use a different pedal system.

Despite this, there are instruments providing a simple but, regarding convenience, well-elaborated power output determination during outdoor cycling. The widespread SRM-System as well as the PowerTap-System are reported to be valid and reliable [7,12], which is not the case for the Polar S710 [14]. However, all these systems do not enable pedal force measurements.

The need for a more-dimensional pedal force measuring device, including power output determination and enabling measurements under laboratory and field conditions, is evident. Therefore, the aim of this study was to develop and validate a new bicycle instrument that enables two-dimensional right and left pedal forces as well as power output measurements with free choice of a pedal system to provide high quality biomechanical data in the field of cycling for research and also sport performance enhancement.

Materials and Methods

Mechanical device

The pedal force measuring device is not built on the basis of a pedal system but as an own mechanical construction which is mounted between the crank and the pedal. The pedal mounting point is “rotated” backwards regarding the pedal trajectory dur-

ing one revolution, which means that there is a 12° shift between the real and the new “virtual” crank arm (Fig. 1). The instrument is based on two sensor systems which determine the magnetic field variations (Hall-Effect) as a result of the displacement (~1/1000 mm) of a small sensor in respect to a magnet. Due to the specific circular construction of the force transmitting elements, the applied force will result in a rotation of the sensor in respect to the opposite magnet. The angular displacement of the sensor in respect to its distance from the rotation centre is so small that the displacement of the sensor is nearly linear.

With two orthogonal located sensor systems, the normal force of the pedal results in a rotation either around one or the other rotation centre. This is due to the alignment of the three web ribs around the geometric rotation centre which transform the force into orthogonal distinct rotations. With this construction, the normal force can be divided into a radial and a tangential part (perpendicular to the pedal axis, Fig. 1), if the sensor systems are adjusted exactly in the direction of these two forces. For this adjustment, the whole system can be rotated around its mounting point at the crank and fixed with two screws. That way the orthogonal radial and tangential forces are decoupled mechanically. Additionally, each sensor is aligned exactly in line with the north-south direction of its magnetic fields of the magnet – and the two magnets are allocated exactly perpendicular to each other. Therefore, a minimal cross-sensitivity is assumed.

The sensor is sensitive in only one direction in relation to the magnetic fields of the magnet (north-south line = zero line). Displacements perpendicular to this direction will not induce any signal. With this, the moments induced by the pedal around the tangential and radial axis, which are orthogonal to the system, will not result in any cross-talk on the force component because the sensor will rotate outward and therefore its displacement is perpendicular to its sensitivity. Therefore, the system should be nonsensitive to the point of force application on the pedal axis, which allows pedals with different axis-length to be used.

Positive tangential force (F_T) was in the pedalling direction and positive radial force (F_R) was in the centrifugal direction. The so-called Powertec[®]-System (O-tec, Bensheim, Germany) allows every pedal system to be screwed on. The mass and dimensions of the system is 230 g and 10.3 cm/7 cm/2.2 cm, respectively. Due to the high-strength material of the construction (3.4365

AlZnMgCu 1.5), nonlinearity is given for $\pm 1\%$. The hysteresis of the sensor is about 1%.

The sensors are fed with 5 V. The voltage range is from 0.5 V to 4.5 V, with a force range from -500 N to 3500 N. With an input resolution of 12 bit and an output range of ± 10 V of the analog/digital transducer, the system resolution is 4.3 N. Using a twofold gain of the analog signal, the resolution was set to 2.15 N.

In this investigation, the Powertec®-System was mounted to the cranks of a SRM-ergometer (Schoberer Rad Messtechnik, Jülich, Germany) and could be mounted onto every type of crank. The signals were transferred via sliding contact from the rotating systems on the bicycle frame. A magnetic switch was used as a position signal of the left pedals top dead centre.

Signals from the Powertec®-System and position switch were sampled with 500 Hz without filtering on a personal computer via an analog/digital data-acquisition card (National Instrument, Austin, TX, USA).

From the pedal force, data measured with the Powertec®-System pedal torque (PT) was calculated as follows.

$$PT = (F_{T_{right}} + F_{T_{left}}) \cdot L \quad (1)$$

where $F_{T_{right}}$ and $F_{T_{left}}$ are the tangential forces of the right and left pedal, and L was the distance in metres from the crank axis to the pedal axis, which is not identical with the SRM-crank length because of the 12° pedal rotation, as mentioned above (Fig. 1). L was 0.170 m in the present study. There is a relation between this angle and the crank length, but the angle of the system mounted at the crank can be modified and therefore the crank length can be modified as well. The SRM-crank can be adjusted to different lengths from 160 mm to 180 mm. We chose a length of the SRM-crank that resulted in a 0.170 m length of the virtual crank arm, in this study. This resulted in an angle of 12° between the real and the virtual crank arm.

The angular velocity of the rotating crank (ω) expressed in radians per second ($\text{rad} \cdot \text{s}^{-1}$) was obtained from the pedalling cadence (P_c) defined in revolution per minute (rpm) recorded by the SRM ergometer:

$$\omega = \frac{P_c \cdot 2 \cdot \pi}{60} \quad (2)$$

where the ratio $2 \pi/60$ stands for the unit transformation of rpm into $\text{rad} \cdot \text{s}^{-1}$.

Finally, the power output (P) expressed in Watts (W) as the mean value for a whole revolution from 0° to 360° (upper dead center) crank angle was calculated as follows:

$$P = PT \cdot \omega \quad (3)$$

Static evaluations

The system was calibrated by loading the right and left pedal in positive and negative tangential and radial direction using ac-

credited masses of 20 kg, 40 kg and 60 kg. For static evaluation, the following tests were conducted.

a) To test the accuracy and the cross-talk of both F_T and F_R , the system was again loaded with 20 kg, 40 kg and 60 kg at crank angles from 0° to 360° with steps of 45° .

b) With the 40 kg load, a second test was performed to quantify the influence of lateral force application on F_T and F_R . The amplitude of the applied lateral force was registered by a piezo-electric force transducer (type 9311 b, Kistler, Winterthur, Switzerland) previously calibrated with a 20 kg mass. The direction of the applied force was controlled by a mechanical inclinometer.

c) To test the influence of different points of force application regarding the lateral spacing between the force application point along the pedal axis and the centre of the hall-sensor, the system was loaded with 40 kg at 90° (F_T) and 180° (F_R) crank angle with one application point in the centre of the pedal and another 3 cm towards the system along the pedal axis. Because highest values during one revolution in real cycling conditions for F_T will occur at 90° and for F_R at 180° crank angle, evaluation simply took place for these two angles.

d) By consecutively loading and unloading the right pedal with a 40 kg mass during 5 s for 15 times with the crank fixed at a 90° crank angle, the reproducibility of measurements of the transducers was tested. This was done only for F_T because the reproducibility is characteristic for the transducer itself and should not differ between the two force dimensions.

e) Finally, with the crank in the 90° position, the signals of the right transducer were sampled after reset for 20 minutes with the system unloaded to evaluate a possible drift of the signal.

Tests b) – e) were performed only with the right handed system because there was no argument for a difference between the identical constructed left- and right hand sided Powertec®-System.

Dynamic evaluations

For the dynamic validation, F_T applied on the right and left pedal were recorded continuously while 9 elite riders performed three 3'30 bouts of pedalling on a SRM-ergometer at 90 rpm with a power output of: (i) 150 W, (ii) 60% of their maximal aerobic power defined in a previous test, and (iii) 320 W. Their mean physical characteristics were 180 ± 6 cm and 68 ± 4 kg. Moreover, their mean maximal oxygen uptake was $71 \pm 6 \text{ mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ and they trained, on average, 20 000 \pm 4000 km each year. Two of them additionally conducted an incremental exercise test with workloads from 75 W up to 500 W with an increment of 25 W for the first and 50 W for all consecutive steps. The exercise bouts lasted 2 min, and subjects rested for 2 minutes in between. The second protocol was implemented to assess a wider range of workloads like those being used in physiological step tests. The cadence was set at 90 rpm during all measurements. The cyclists used their own clipless pedal systems. The data sampling rate for the pedal forces was 500 Hz. From unfiltered raw data, single data pieces from 0° to 360° crank angle have been cut, time normalised and summed up for 30 crank revolutions to get a representative ensemble average of every exercise bout.

At the same time, power output was measured via the SRM-crank on the SRM-ergometer. This signal was sampled with 1 Hz on a PC. Signals of both devices – Powertec®-System and SRM-System – were synchronised by manually marking the beginning and the end of each 30 s recording bout in the SRM data. The accuracy of the professional version of the SRM-System, which uses four strain gauges, is reported to be 2.3% [7]. The SRM-crank used in this investigation was the scientific version with eight strain gauges, where the manufacturer claimed accuracy is lower than $\pm 0.5\%$.

Peddalling cadence was provided and registered by the SRM-ergometer, and subjects were encouraged to keep it constant.

Statistics

The accuracy of the system was analysed by assessing the errors of measurement (root-mean square, mean, one standard deviation and range of values) between the force applied and the force calculated by the system during the static measurements (a, b, c, d) and between the power output given by the SRM and that calculated on basis of the pedal force data of the Powertec®-System. The percent error was calculated as $([\text{estimate-criterion}]/\text{criterion})$. The drift (e) was quantified by linear regression between force and elapsed time. The validity of the power output measurement of the Powertec®-System was analysed in comparison with the reference power measurement of the SRM using linear regression analysis. The coefficient of determination (R-square) and the regression line in respect to the equality line was used to characterise the relationship between and the agreement of the measurements of both devices. To further assess the agreement of the measurements of both systems a Bland-Altman plot was constructed [2]. For the Bland-Altman plot two standard deviations, representing 95% confidence limits, were used.

Results

Static evaluations

Fig. 2 shows the difference (error) between the applied force (load) – representing the criterion – and the calculated force – representing the estimate in relation to the crank angle (a). The mean error, the RMS error and the range of error are presented in Table 1. The mean error was $-0.87 \pm 4.09\%$ (mean ± 1 SD) for the tangential and $-1.86 \pm 6.61\%$ for the radial direction. This corresponded to a RMS error of 4.12% for F_T and 6.77% for F_R .

The cross-talk produced by F_T on F_R was $\pm 6.56\%$ and $\pm 3.23\%$ vice versa.

The influence of lateral force (b) on F_T and F_R , investigated by applying 100 N perpendicular to the pedal forces, was 7.77 ± 4.88 N and 6.43 ± 5.12 N, respectively, or $2.39 \pm 1.5\%$ and $2.36 \pm 1.28\%$ when expressed in relative values.

The influence of different force application points (c) regarding the lateral spacing between the pedal centre and the system was 2.37% for F_T at a 90° crank angle and 10.29% for F_R at a 180° crank angle, with the applied force at pedal centre condition as 100%.

The reproducibility error (d) of the transducers was described by a standard deviation of ± 3.05 N or $\pm 0.74\%$ (range 9.31 N or 2.37%) when it was loaded 15 times with 40 kg and F_T was measured.

The drift (e) was -0.02 N \cdot min⁻¹ for both F_T and F_R .

Dynamic evaluations

Tangential and radial forces applied on both pedals during the pedalling test used for dynamic validation could be described as follows: F_T was positive during the downstroke phase of the pedal with peak value reaching 184 N and 436 N at about a 90° crank angle for 100 W and 500 W, respectively (Fig. 3). During the upstroke phase of the pedal, F_T was negative and therefore induced a counter movement with about -71 N and -8 N at a 267° and 296° crank angle for 100 W and 500 W, respectively. F_R was positive during the second half of the downstroke phase of the pedal with peak value reaching about 131 N and 327 N at a 136° and 130° crank angle for 100 W and 500 W, respectively. While passing the top dead centre, F_R was negative with about -41 N and -174 N at a 22° and 39° crank angle for both mentioned loads.

In the dynamic validation test, the difference between the calculated power from the Powertec®-System and the SRM-System ranged from -15.6 W to 10.6 W for absolute values and from -6.25% to 6.41% for relative values. The mean absolute and relative difference over all loads and subjects was 4.95 ± 4.25 W and $2.32 \pm 1.95\%$, respectively.

In the incremental exercise test, the difference between both systems ranged from -3.87 W to 13.5 W for absolute values and from -4.27% to 2.94% for relative values. The mean absolute and relative difference over all loads and for both subjects was 5.23 ± 3.76 W and $1.92 \pm 1.04\%$, respectively.

The relationship between the power output values measured by the Powertec®-System and SRM is shown in Fig. 4. A considerable high and also significant R-square as well as the good congruence of regression and equality line was obtained. There was a small overestimation of power measured with the Powertec®-System compared with SRM (1.69 W per 100 W workload increase).

Fig. 5 presents a Bland-Altman plot of the differences between Powertec®-System and SRM-System for all data points collected throughout the range of power outputs. To show the influence of power on the difference between both systems, a regression line has been added.

Most of the error-values lay within the 95% limits of agreement.

Discussion

The accuracy of the static measurements was satisfactory when looking at the mean percent error below 1.9% for both directions and a RMS error below 4.12% for F_T and below 6.77% for F_R . This error was comparable to the $\pm 5\%$ mean percent error obtained by Broker and Gregor [4] and Newmiller et al. [16] or to the $> 6\%$ RMS error reported by Mornieux et al. [15] for other pedal force measurement systems. The mean absolute error of -0.22 N (F_T)

Fig. 2 Accuracy of the tangential (F_T) and radial (F_R) component in relation to the crank angle. Dotted lines represent the applied loads, values represent positive or negative deviation from the applied load at a certain crank angle. At 0° (360°)/ 180° , the tangential component and at 90° / 270° , the radial component do not respond to the loads because this is perpendicular to their main sensitivity.

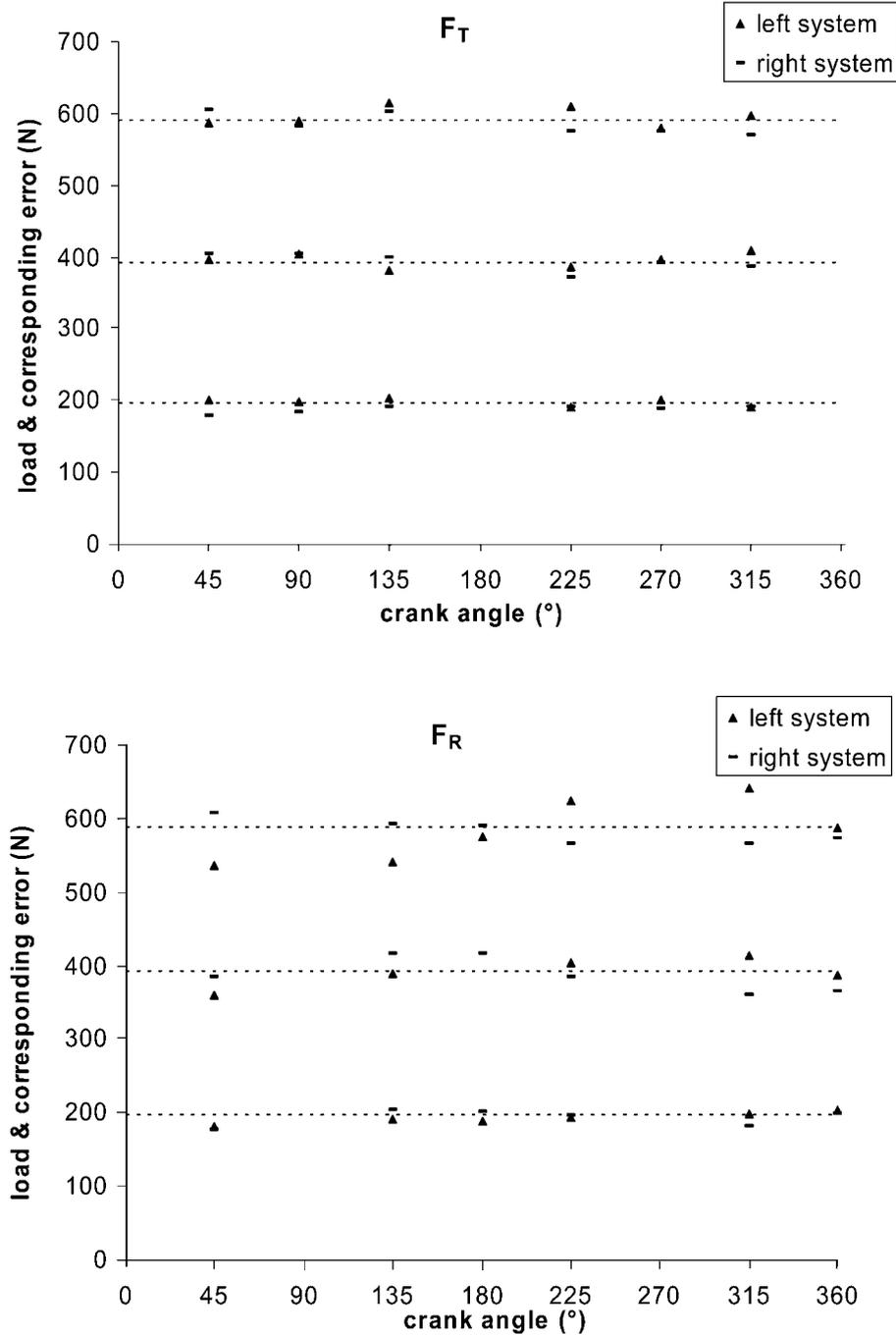


Table 1 Difference (error) between applied Force and calculated Force (mean over all loads and crank angles)

	<i>Mean ± 1 SD</i>		<i>Range</i>		<i>RMSE</i>	
	<i>Absolute (N)</i>	<i>Relative (%)</i>	<i>Absolute (N)</i>	<i>Relative (%)</i>	<i>Absolute (N)</i>	<i>Relative (%)</i>
F_T	-0.22	±11.48	-0.87	±4.09	47.87	20.25
F_R	-4.25	±21.60	-1.86	±6.61	103.82	25.92

and -4.25 N (F_R) was comparable to the accuracy values of the dynamometer presented by Boyd et al. [3]. Evaluating these values in light of the literature, it has to be pointed out that most of the pedal force measuring systems reported there determine forces on the pedal coordinate system (F_x , F_y , F_z). Therefore, a

one-to-one comparison is not appropriate. Furthermore, it may be criticised that a number of papers do not specify which load the Newton error refers to [3,24]; others do not provide the exact error or sufficient information about the calibration procedure [1,4,18,26].

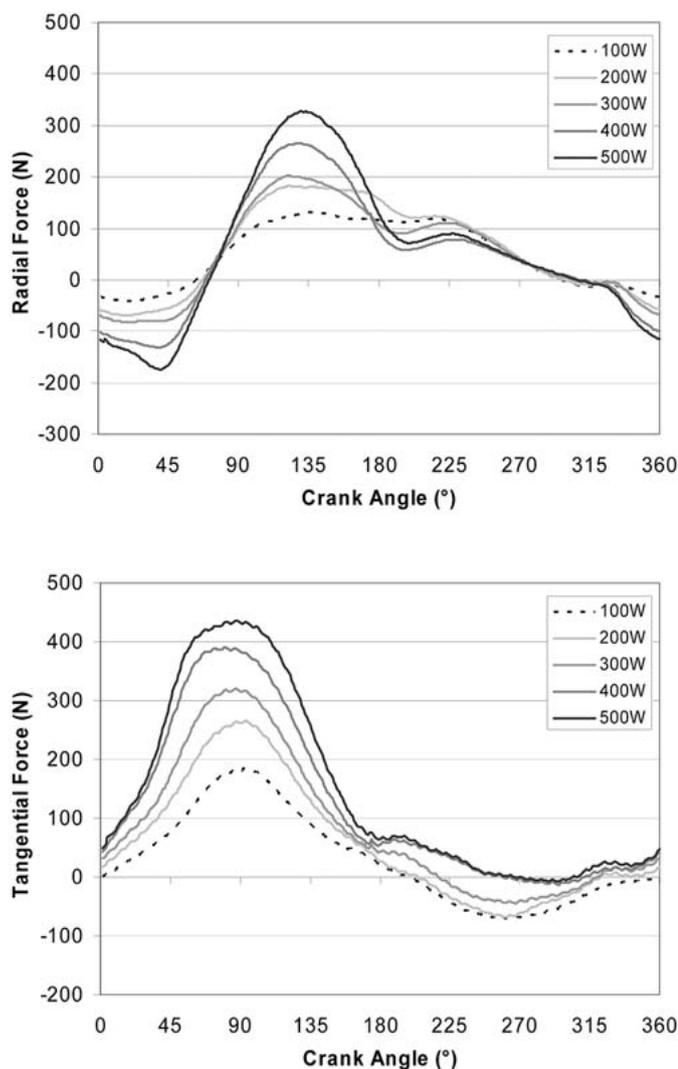


Fig. 3 Typical tangential and radial forces applied on the left pedal during one crank revolution at different power outputs between 100 and 500 Watts at 90 rpm (data averaged for 30 cycles).

The cross-talk values below $\pm 3.3\%$ for F_T and below $\pm 6.6\%$ for F_R , the good reproducibility and drift values and the fact that lateral force had little influence on pedal forces document that the accuracy of this instrument is sufficient enough to conduct scientific and applied measurements in the field of cycling biomechanics. The 2.4% lateral force influence would have been even less because the application of the lateral force might not have been exactly perpendicular to F_T and F_R even if the direction was controlled manually by an inclinometer.

The influence of different lateral force application points is negligible for F_T . The radial component is somewhat sensitive for changing application points. But the distance of 3 cm between the two points where the load was applied on the pedal axis, in the current study, is rather high and threefold higher than the 1 cm lateral spacing variation of different pedal models. Furthermore, this effect could be minimised by calibrating the instrument exactly with the spacing shown by the subsequently used pedal.

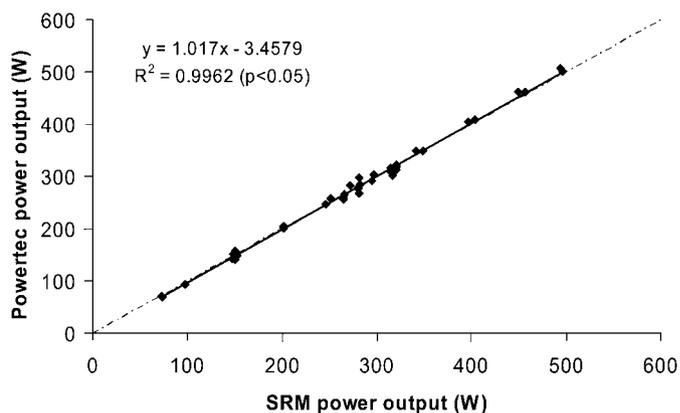


Fig. 4 Relationship between the power output measured by the Powertec®-System and that given by the SRM for all power measurements for all subjects (data averaged for 30 cycles; dotted line: equality line).

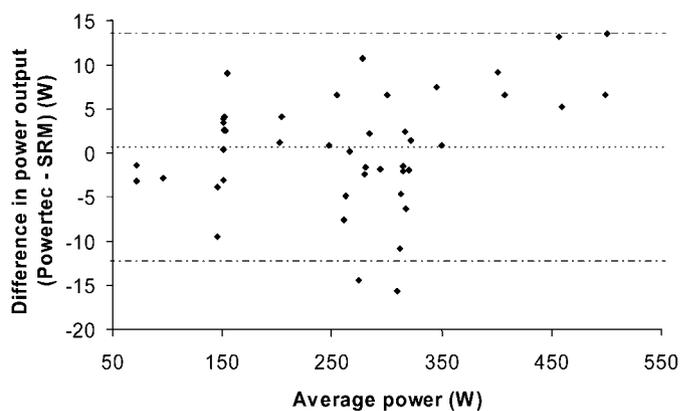


Fig. 5 Bland-Altman plot (differences against average of Powertec®-System and SRM measurements) with 95% limits of agreement (broken lines), mean different value (dotted line) and regression line. Values represent all power measurements for all subjects (data averaged for 30 cycles).

The orientation and amplitudes of pedal forces determined for loads ranging from 100 up to 500 W over a whole pedal revolution were in agreement with previous data reported in the literature for the tangential force at comparable cadence and power output [20,21].

The 2.32% error in the power output determination compared to the SRM-crank was satisfactory and underlined the advantage of the present method for power output measurements in cycling, as the reference method used in this study was one of the most valid and reliable wattmeter [7,12]. Furthermore, according to linear regression analysis, the Powertec®-System showed a significant relationship with the SRM-ergometer ($R^2 = 0.99$; $p < 0.05$). Beyond the correlation with the SRM-ergometer, the Powertec®-System was in good agreement to this instrument as (i) the values of the relationship between these two methods lay close to the equality line, and (ii) most of the distribution of the differences between both methods was within the ± 2 SD limits of agreement [2]. These results further support the validity of the measurement of power and, hence, tangential forces.

It should not be concealed that the method presented brings about some methodological constraints. The lack of medial-lateral pedal force measurements did not allow a complete 3D pedal forces analysis. However, this force remains considerably lower than the two other dimensions and could even be assumed to be negligible during the upstroke, according to the literature [3,4]. Moreover, the present system shows cross-talk in contrast to other systems where this problem is compensated [3,16]. However, the error in the measurements due to that phenomenon was tested and found to be less than $\pm 6.6\%$. Even if the cross-talk induced a substantial error principally for the radial forces, this effect on the tangential forces was low ($\pm 3.3\%$), which implies a negligible error in the power output determination.

Nevertheless, overall the errors found on force measurements were comparable to the literature. Moreover, the present method offers the possibility for pedal force measurements and power output during laboratory and, in the near future, also during field conditions. To realise the latter, the problem of data storage has to be solved, but this is not a problem of measurement accuracy. Current developments centre on data transfer and storage via recently available compact-flash data acquisition cards (National Instrument, Austin, TX, USA) and PDA. Indeed, this bicycle instrument is not only adaptable to the crank of the SRM-ergometer but also to the different types of cranks of common bicycles and could, therefore, also be used in multiple testing situations. Therefore, this system presents more measurement possibilities than comparable existing instruments providing either only pedal force measurements in the laboratory [3,4,11,16,24,26] and potentially in field conditions [1,19], or only valid power output measurements as, for example, the SRM-System [7,12] or the PowerTap-System [7].

Moreover, this system is prepared for every pedal system to be screwed on, which allows cyclists to use their own pedals and shoes to which they are accustomed instead of readjusting the foot position on the pedal.

To conclude, measurement possibilities provided by the Powertec®-System could be useful for biomechanical analysis in cycling research, as pedal force and power output measurements were validated in the present study. Furthermore, this method potentially enables field measurements with all pedal systems. So investigations in real cycling conditions might be possible in the near future.

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