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RESEARCH ARTICLE

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A novel method based on first principles to determine the accuracy and reliability of force measurements reported by bicycle power meters

Ryan Worn and Dan B Dwyer[1]✉

Abstract

The accuracy and reliability of instrumented bicycle crank systems (i.e. power meters) is an important consideration for sport scientists who evaluate cycling performance and pedalling biomechanics. Many crank systems report power and or force/s on the left and right crank arms separately, or indexes of pedalling effectiveness, although crank systems that have genuinely independent force transducers on the left and right crank arms are rare. There is a need to be able to evaluate the accuracy and reliability of the measurements of power meters without the requirement for expensive and or complex instrumentation. The present study describes a relatively simple and novel method of assessing the accuracy and reliability of measures of crank angle, radial force and tangential force. The method is demonstrated in its application to an instrumented crank system (Axis Cranks ™). Reported crank forces were compared with actual applied forces to determine accuracy and some procedures used to assess the measurement of force were duplicated to determine reliability. The crank system measured crank angle with an average RMS error of 1.65 degrees across pedalling rates of 30-150 r/min. The absolute error of radial and tangential force measurements were 6% and 3.2% respectively (RMSE) and the relative error (accuracy of change in force) of radial and tangential force were 1.48% and 0.25% respectively (RMSE). Repeated measurements of force were found to be highly reliable (intra-class coefficient > 0.99). The method presented in this report could be used to evaluate the accuracy and reliability of other power meters and instrumented crank systems.3

Keywords: validity, crank angle, pedalling technique

✉**Contact email:** dan.dwyer@deakin.edu.au (DB. Dwyer)

[1] Centre for Exercise & Sport Science. Deakin University, Australia

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Introduction

The technology used to measure pedal forces and pedalling technique may be limited by precision, which in turn may have hindered the understanding of the importance of pedalling technique for cycling performance. For example, some of the existing research on pedalling technique has not measured left and right pedal forces in a truly independent way (i.e. using separate force transducers on left and right cranks) (Carpes et al. 2010). Further, few studies have been able to report tangential and radial forces independently (See review by Bini et al. 2013), and the conclusions of some studies have been based on either a relatively small number of measurements, or averaged measurements in each pedal revolution (Bini et al. 2013).

Historically, lab based versions of power meters capable of recording both the left and right forces at a high resolution have proven too bulky with the need to be constantly tethered to a computer and have therefore proven to be unusable in the field (Mornieux et al. 2006). However, advances in technology have made it possible for sport scientists and consumers to obtain power meters that are suitable for use in the field (e.g. Garmin Vector™ pedals and Pioneer Power Meter™). Many systems, such as the SRM™ and Quarq™ bicycle cranks, presently only have the capability to record data from the crank spider, or one of the crank arms, and not from both cranks independently. However, some of these systems report left and right pedalling forces as well as indexes of pedalling effectiveness or efficiency, without the necessary recording capabilities to do so properly. More recently, some power meters (Garmin Vector™ pedals, Stages™ power meter, Pioneer Power Meter) capable of measuring force from both the left and right legs have become available and claim to measure left and right balance and pedalling smoothness. If the measurements made by these consumer power meters are to be used by sport scientists and cyclists, then there is a need to determine the accuracy of their measurements. The ability of researchers to make conclusions about the relationships between pedalling technique and cycling performance depends upon the accuracy of the instrumented crank systems. Cyclists and coaches also need to understand the limitations of these systems and their reported measurements in order to influence decisions about pedalling technique and training.

Due to the cyclical (i.e. not static) nature of pedalling, the authors decided not to employ a static method to determine force accuracy (Wooles et al. 2005; Alexander et al. 2015) and instead created a novel and simple dynamic calibration method that could be used to determine the accuracy of force measurements (both radial and tangential) based on crank angle. This first principles dynamic calibration method could be used for other crank systems requiring force accuracy determination and does not rely on the additional use of one or several "gold standard" power meters to compare against (Bouillod et al. 2016) or the use of complex dynamic calibration rigs (Gardner et al. 2004).

Therefore, the purpose of this study was to design and evaluate a simple dynamic calibration method that could be used to determine the accuracy of force measurements (both radial and tangential) of an instrumented crank system or consumer power meter. The authors sought to avoid the need for a calibration rig or comparison power meters and instead took a "first principles" approach. The calibration method was evaluated on an instrumented bicycle crank that is designed to be used for research purposes in the lab and in the field (Axis Cranks, Swift Performance, Australia). The system purports to accurately measure pedal forces (tangential and radial) on both the left and right crank arms independently and at a relatively high sample rate (100 Hz). To date only four studies have reported the use of this crank system (Barratt 2011; Brooks et al. 2013; Giorgi et al. 2015; Giorgi et al. 2015a), however there is no published data concerning the crank system accuracy.

The primary hypothesis was that the instrumented bicycle cranks measure crank angle and crank forces with an error of less than 2.0 %. The secondary hypothesis was that the reliability of measurements of crank forces is greater than 0.95 (intra-class correlation coefficient).

Methods

The present study did not involve the use of participants. The methodology is one based on the use of first principles to determine the accuracy and reliability of the crank system. The authors are confident that the present study followed closely the ethical considerations highlighted in the study of Harris and Atkinson (2011). All data collection trials were performed in the same climate controlled laboratory by the authors.

Assessment of cranck angle

The right hand crank arm was fitted with a small retro-reflective marker at the centre of the bottom bracket (axis of rotation) and at the centre of the pedal spindle hole. The instrumented bicycle crank software measured and reported crank angle at 100 Hz during the assessment procedure (described below). The angle of the crank arm was calibrated in the Axis Crank software before testing, using a digital inclinometer (Bevel Box Inclinometer). A motion analysis system (VICON, Denver, USA) that has been shown to be accurate way to measure motion (Windolf et al. 2008), was used as the "gold standard" measurement of crank angle. The motion capture system measured and reported the movement of the retro-reflective markers at 100 Hz, during the assessment procedure. The relative motion of the markers was used to determine crank angle and thus could be used to determine pedalling rates.

The crank angle assessment procedure involved rotating the crank arm free of retroreflective markers by hand during a series of trials, at or close to the following pedalling rates; 30, 60, 90, 120 and 150 r/min, which were maintained for at least 30 seconds each. A metronome was used to set the target pedalling rate at which the cranks were rotated. To assist with the accurate synchronisation of data from both the motion capture and instrumented bicycle crank systems, the crank movement at each pedalling rate began with a ~45º 'back pedal' (counter clockwise). Crank angle data collected from the crank arm fitted with retroreflective markers at 100 Hz was compared from both systems across 15 pedal revolutions.

Assessment of force

Assessment of the accuracy of pedal force measurements was completed by comparing forces reported by the instrumented bicycle crank system against known forces applied by masses (weight plates) attached to the pedals by chain and shackle. Before all testing began, the cranks were calibrated in the bicycle crank software using the manufacturer's instructions. The bicycle was elevated from the ground (Figure 1), which allowed for total masses of approximately 10, 20, 40 and 80kg (inclusive of weight plates and chain and shackles) to be attached to both the left and right cranks. Prior to attachment, the weight of each mass (including the chain and shackles) was determined to an accuracy of 0.01Kg using calibrated scales (Tanita Tokyo, Japan). For table presentation purposes, the weights have been rounded to the nearest whole number, however calculations were performed on exact weights. The use of chain and shackle meant the force was constantly applied in a vertical (downward) direction, allowing correct calculation of radial, tangential and resultant forces for each crank. After calibration and attachment, in order to rotate the cranks without applying additional force, the flywheel (connected to the cranks via the bicycle chain) was gently rotated anticlockwise by hand (Figure 1). One full rotation of the cranks (360°) was required in order for each hanging weight to apply forces both radially and tangentially at each degree of the full crank rotation. The researchers were aware of the possibility of potential "sway" in the applied weights and took care to avoid this by slowly rotating the flywheel. The average cadence across all trials was 0.57 r/min ± 8%). The forces reported by the instrumented bicycle crank system were compared with the actual radial and tangential forces applied, as determined by trigonometric calculations based on measured crank angle and applied mass.

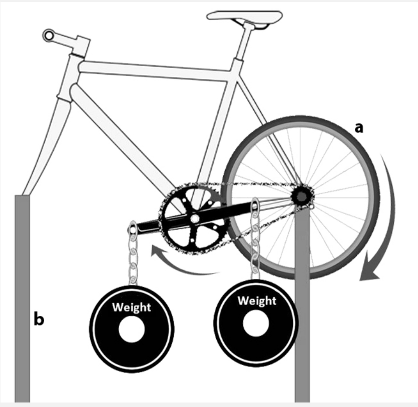

Figure 1. A graphical representation of the force testing apparatus. Arrows show the direction of motion with force gently applied by hand (a). The bicycle was suspended by supports shown at (b).

Data Analysis

All raw (un-filtered) data (crank angle and force) was exported to a spreadsheet for analysis (Excel, Microsoft, USA). Accuracy of pedalling rate, tangential and radial force are reported as mean bias, the standard deviation of the bias and the root mean squared error. These measures of accuracy were calculated from all of the data collected. Reliability was reported as intra-class correlation coefficients, calculated between serial measurements of force.

Results

The instrumented bicycle crank system measured crank angle with an overall bias (mean ± SD) of -0.23º ±1.56º (Table 1). The magnitude of the bias was not related to pedalling rate, although the variance (SD) of the bias and the RMSE appear to increase with pedalling rate. The average RMSE of crank angle for all pedalling rates was 1.65º.

Table 1. The accuracy of angle measurements by the instrumented bicycle cranks. SD is standard deviation. RMSE is root mean squared error.

Pedalling Rate (r/min)	Mean Bias (Crank angle º)	SD (Crank angle º)	RMSE (Crank angle º)
30	-0.69	0.85	1.10
60	0.61	1.76	1.87
90	0.07	1.41	1.41
120	-0.49	1.90	1.96
150	-0.67	1.89	1.92
Average	**-0.23**	**1.56**	**1.65**

Accuracy of force measurement was assessed for radial and tangential forces, for left and right cranks, and in absolute and relative terms. The measures of accuracy of the left and right cranks were very similar (<2% different) and were averaged in order to simplify the presentation of the results. When comparing the radial forces reported by the instrumented bicycle crank system to the actual applied forces, the overall bias (mean ± SD) was 1.05 ±14.51 N and the RMSE was 15.25 N (Table 2). These values are averages across the range of applied forces (10 – 80 Kg) and so in relative terms, when compared to all of the applied forces, the RMSE for radial force was 6.0%.

These errors represent the difference between the reported and actual (absolute error) radial forces, however when measuring the magnitude of change (relative error) in radial force, the overall bias (mean ± SD) and RMSE were -2.03 (±6.61) N and 6.66 N. When the relative error is expressed as a percentage of the applied force, the average overall error is 1.48%. Relative error is at least as important as absolute error, because the results reported by systems like this are most commonly used to identify changes in force over very short periods of time (e.g. within a pedal stroke) and over long periods of time (e.g. throughout an event or over the course of several months or years of training).

Table 2. The accuracy of radial force measurements by the instrumented bicycle cranks. Absolute error results represent the difference between reported and actual forces. The relative error represents the difference between reported and actual change in applied force. Measurement error is the relative error, expressed as a percentage of the actual change in force. SD is standard deviation. RMSE is root mean squared error.

Applied Mass (kg)	Absolute Error			
	Mean Bias (N)	**SD (N)**	**RMSE (N)**	**RMSE (%)**
10	4.26	5.28	6.84	7.9%
20	4.05	9.48	10.39	6.3%
40	0.78	16.92	16.94	6.2%
80	-4.91	26.37	26.82	3.6%
Average	**1.05**	**14.51**	**15.25**	**6.0%**
	Relative Error			
	Mean Bias (N)	**SD (N)**	**RMSE (N)**	**Measurement Error (%)**
10	-0.81	1.34	1.53	1.10%
20	-0.53	2.13	2.10	0.33%
40	-3.06	6.08	6.53	2.33%
80	-3.71	16.91	16.48	2.18%
Average	**-2.03**	**6.61**	**6.66**	**1.48%**

Errors associated with the measurement of tangential forces appear in Table 3. Bias (mean ± SD) and RMSE for comparisons between reported and actual forces (absolute) were 0.66 (±1.41) N and 1.57 N. When comparing the reported with the actual change in force (relative error) the overall bias (mean ± SD) and RMSE were -0.02 (±0.65) N and 0.63 N. When the relative error is expressed as a percentage of the applied force, the average overall is 0.25%.

The reliability of force measurements was assessed by completing the 80 Kg (applied mass) validation trial on two separate days. The reliability of measures of radial and tangential forces are high, as the intra-class correlation coefficients were all above 0.999 (Table 4).

Table 3. The accuracy of tangential force measurements by the instrumented bicycle cranks. Absolute error results represent the difference between reported and actual forces. The Relative error represents the difference between reported and actual change in applied force. Measurement error is the relative error, expressed as a percentage of the actual change in force. SD is standard deviation. RMSE is root mean squared error.

Applied Mass (kg)	Absolute Error			
	Mean Bias (N)	SD (N)	RMSE (N)	RMSE (%)
10	0.35	0.49	0.63	4.4%
20	0.39	0.63	0.76	2.9%
40	0.55	1.38	1.49	2.2%
80	1.33	3.16	3.42	3.2%
Average	**0.66**	**1.41**	**1.57**	**3.2%**
	Relative Error			
	Mean Bias (N)	**SD (N)**	**RMSE (N)**	**Measurement Error (%)**
10	-0.07	0.17	0.18	0.17%
20	-0.09	0.25	0.26	0.63%
40	-0.10	0.51	0.51	0.02%

Table 4. The reliability of force measurements from the instrumented bicycle cranks. Reliability is reported as the intra-class correlation coefficient between the forces reported by the bicycle crank system, across two separate trials, of an applied mass of 80 Kg, for all angles (0 - 359o). * indicates statistical significance of p<0.05.

	Radial Force		Tangential Force	
	Left	Right	Left	Right
Intra-class correlation coefficient	1.000*	0.999*	1.000*	1.000*

Discussion

The present study provides a demonstration of a method that can be used to determine the accuracy and reliability of an instrumented crank system or a power meter. The methods used to evaluate measurements of force are relatively simple, however the method we used to evaluate the accuracy of crank angle measures was more complicated. The results confirm the primary and secondary hypotheses, that the crank system in question measures crank angle and crank forces with a high degree of accuracy and reliability. Measures of tangential force are more accurate than radial force and measures of change in force are more accurate than the reported force compared to the actual applied force. For the present crank system, the results for the left and right cranks were so similar, they were combined for convenience, but it is important to report left-right results separately when they are different. The results from the present study provide valuable information about the accuracy of a commercially available instrumented crank system and can be used to evaluate and compare with other power meters.

Historically, power measurement devices were limited to measuring forces in one dimension only, with strain gauges fitted to either the crank or pedal (Daly and Cavanagh 1976; Kunstlinger et al. 1977; Brooke et al. 1981). As technology has progressed, measurement devices have improved and many devices have become capable of measuring forces in three dimensions (Hull and Wooten 1996; Newmill et et al. 1988). However, many of these devices have been explicitly constructed for use within dedicated laboratories and lack the ability to measure both radial and tangential forces independently on both the left and right side of the bicycle at high resolution (Alvarez and Vinyolas 1996; Rowe et al. 1988). Further, many of these power measurement devices have proven cumbersome and have required the use of cables (Alexander et al. 2015; Newmiller et al 1988; Diefenthaler et al. 2012; Osorio et al. 2007), force platforms (Mornieux et al. 2006) and unusual ergometers (Reiser et al. 2003) all of which constrain the real-world applicability of such devices. Although there are several reports of the accuracy of relatively simple commercially available power meters and comparisons between them (Abbiss et al. 2009; Bertucci et al. 2005; Duc et al. 2007; Staplefeldt et al. 2007; Wooles et al. 2005; Bouillod et al. 2017), there are very few reports of the accuracy of commercially available research grade bicycle crank systems that measure crank angle, and tangential and radial forces on the left and right crank arms independently at a high resolution.

Stapelfeldt et al., (2007) reported on the accuracy of the Powertec™ system against another commercially available power measurement device as their “gold standard” (SRM™ power meter). Small errors were reported (2 % error for force measures) when compared against the SRM™, however this approach raises the possibility that both systems had a similar and yet unknown error. Further, Alexander et al., (2015) assessed the accuracy of the JA:Ped3™ pedal based instrument against a set of SRM™ cranks and a PowerForce system during the same dynamic trial and concluded that the JA:Ped3™ presented as an accurate force measurement device, with deviations of less than 3% when compared to the SRM™ cranks.

Moreover, Bini et al., (2011) reported on the accuracy of a pedal based instrument for measuring pedalling forces (SGI pedals) and reported large errors for measures of power (~21%) but smaller (3-16%) mean biases in measurement of force. Similar to both the Stapelfeldt et al., (2007) and Alexander et al., (2015) studies, this study also made the assumption that SRM™ cranks are a suitable “gold standard” for comparison. In addition, the assumption was made that the SGI™ cranks were more accurate than the SRM™ cranks and concluded the pedal based measurement of pedalling forces was the superior system. Although the SRM™ cranks have been shown to be a valid and reliable tool (Wooles et al. 2005; Gardner et al. 2004; Bini, et al. 2011) for measurement of power, it is questionable that these cranks can be considered the “gold standard” to compare other power measuring devices against.

Problems arise when new types of power measuring devices are compared against existing devices incapable of performing the same measures. For instance, the cranks presently in question are currently (to the best of this author’s knowledge) the only cranks capable of measuring both radial and tangential forces at 100 Hz from both cranks independently.

With the above in mind, the present study took a novel "first principles" approach for the validation of force measurements by using weights of known mass to apply known forces and compared these with the forces reported by the instrumented bicycle crank system. When the cranks are unloaded and rotated, the crank system reported very small (0-5 N) radial forces that were dependent upon the crank angle. This "zero offset error" was always present and was not changed by a recalibration process. No such error was present for tangential forces and none of the results reported here were adjusted for this error. Despite this error, the bias for both radial (1.05 N) and tangential (-2.03 N) forces were relatively small. The standard deviation of the bias in radial force was relatively large (14.51 N), which represents the least accurate feature of this crank system. This variance is in large part due to the fact that the instrumented bicycle crank system, reports unfiltered measurements. Indeed, the raw data demonstrate a high frequency oscillation (~20 Hz) about a mean value. This oscillation could be filtered, although no filtering was used in the present study. This oscillation was also present in the tangential force data, but it was much smaller in amplitude and hence the SD of the bias and the RMSE were also smaller.

A crank force measurement system is used primarily to measure changes in force throughout a single crank rotation or throughout the course of a prolonged exercise task (Bini et al. 2013). Therefore, the system must be able to accurately measure changes in force. When the reported change in force was compared with the actual change in force (relative error), the accuracy of the system generally improved. Bias for radial forces increased, but all other measures of accuracy improved. Importantly, the average difference between the reported and actual change in force for radial and tangential forces were 1.48 % and 0.25% respectively.

The results that indicate the level of agreement of force measurements from two identical but separate trials, provide an indication of the reliability of the system. The serial measures of force had a high level of agreement (all intra-class correlation coefficients > 0.998), indicating high reliability.

The design of this study has some limitations. We were unable to develop a simple "first principles" method to assess crank angle measurements. We used a method that is valid, but it would not be possible for others to use without access to a motion capture system. Some power meters do not measure or report crank angle and so this limitation may not apply on all cases. There is at least one power meter that measures the medio-lateral forces that the foot applies to the pedal. The present study did not assess the accuracy of this specific type of force measurement.

Practical applications

The novel first principles force calibration method described here presents a relatively simple, fast and cost-effective way of determining the accuracy of force measurements in crank based power meters.

The instrumented bicycle crank system in question provides reliable and accurate measurements of crank angle, radial and tangential forces. The errors associated with tangential force are smaller than for radial force. The errors associated with relative measurements of force (change in force) are smaller than for absolute measurements of force.

Due to the high accuracy and relative portability, the Axis™ instrumented cranks, may be used for many applications including competitive sport, injury rehabilitation and as a sophisticated laboratory device capable of measuring forces in two-dimensions at a relatively high sample rate.

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Conflict of Interest

This research did not receive any funding.

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