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ORIGINAL ARTICLE

A user-friendly calibration system for bicycle ergometers, home trainers and bicycle power monitoring devices

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Abstract In this study, a new system for the calibration of bicycle ergometers, home trainers and bicycle power monitoring devices is described. This system contains a portable calibration rig as well as a specialised calibration software and is designed for easy and efficient use directly on-site by non-expert personnel. Key features of the calibration rig include a cradle used to implement a torque reaction measurement technique, roller casters, sliding coupling, and crowned splines to facilitate and speed up the calibration process. The maximum power uncertainty delivered by the calibration rig for a nominal power level range of 50–600 W is ±0.9%. A software to guide users through the calibration process and generate calibration charts is described. To illustrate how the calibration system is typically used, the calibration charts of two different brands of home trainers have been obtained, and the power output measurement accuracy of two bicycle power monitoring devices has been determined. Power discrepancies were noted. The results in this study reveal that the calibration system is an effective tool in characterising the behaviour of home trainers.

Keywords Bicycle · Calibration · Ergometers · Home trainers

1 Introduction

With the introduction of new measurement technologies in sports such as cycling, power (expressed in Watts) has become the reference metric to quantify athletes' effort levels. In hospitals and rehabilitation centres, medical bicycle ergometers and home trainers use power units to set workloads for patient assessment. Sports research centres currently use a wide variety of equipment with power output as the controlled parameter. For daily training purposes, a large variety of personal home trainers use power to set and measure workloads. On the road, power monitoring devices with instrumented components such as the SRM™ crank, the PowerTap™ hub or the Ergomo™ bottom bracket are widely used. The widespread use of this equipment raises the critical question of the need for periodic calibration.

It is well established that any type of instrument used for measurement must be checked and periodically recalibrated. The interval between recalibrations depends on the type of equipment, the operating conditions, frequency of use and most importantly on how critical it is for the user to obtain accurate estimations of workload and power. In medicine for example, it is easy to imagine the potentially disastrous consequences of an inappropriate workload for patients exercising on bicycle ergometers following surgery. For athletes, the use of inaccurate training devices or power monitoring systems could result in under- or overtraining. For sports science, periodic calibration is required to guarantee the accuracy of the published data.

The calibration of bicycle ergometers and home trainers has been studied in the past and a few calibration rigs have been described in the literature. These calibration rigs apply a known load to the equipment to be calibrated and act as dynamometers. They estimate the true workload using torsion spring deformation [6] or a torque reaction measurement technique [1, 2, 4, 6–8]. The calibration rigs described in these authors' published research were essentially designed for use in the laboratory by skilled and

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experienced personnel. The calibration rig proposed by Cumming and Alexander [2] and the one proposed by Stein et al. [7] must both be precisely balanced with weights. In the calibration device described by Clark and Greenleaf [6], the pedal brake assembly needs to be removed from the bicycle ergometer and installed on a lathe. The calibration rig introduced by Woods et al. [8] requires a pallet truck to be moved around. No previous work has described any specialised calibration software to guide the user during the calibration procedure. To the authors' knowledge, two calibration rigs are commercially available: Lode Calibrator 2000 (Lode B.V, The Netherlands) and Cycloergometer Calibrator (Vacu-Med, USA). They are portable and designed for cycle ergometer calibration.

The new calibration system (calibration rig and calibration software) proposed in this paper was designed to meet the specific needs of the authors for testing and calibrating cycling power measurement equipment. It was also designed to meet the needs for periodic and frequent accuracy checks by coaches and athletes at the Canadian National Cycling Training Centre in Bromont (Canada). The overall characteristics of the proposed calibration system distinguish it from what has already been described in the literature. These characteristics are the following:

- Provides accurate calibration data.
- Capable of calibrating bicycle ergometers, home trainers as well as bicycle power monitoring devices.
- Easy and efficient to use directly on site by a non-expert.
- Portable.

The objective of this study is to report on the design and performance of this new calibration system. Technical insights and details are given for all aspects of the calibration rig design as well as for practical aspects of its use, thus providing researchers and the sports community with a means of designing and building a calibration rig to meet their specific needs and requirements. Sample calibration test results are given for home trainers and for SRM powermeter and PowerTap hub units. These test results are provided to demonstrate the ability of the calibration system to provide useful information, but not with a goal of supporting an exhaustive study of the performance of these devices.

2 Methods

2.1 Description of the calibration rig

The main calibration rig components are shown in Fig. 1. It is basically a torque reaction measuring device that is connected to the left hand side of the crank axle with a driving shaft. The speed-controlled motor provides the required torque to drive the crank axle at a pre-selected rotating angular velocity that is independent from the load imposed by the bicycle ergometer or home trainer. The calibration process consists of comparing the power delivered by the calibration rig to the power displayed by the equipment being calibrated.

Figure 2a is a diagram of the calibration rig. The 1.5 kW aluminium electric motor (Brook Crompton model W-DA145T) is bolted to an inline 14-to-1 speed reducer (Hansen model SCE15B14U-145TC). The speed of the motor is controlled by an electronic drive (Siemens Micromaster 440 model 6SE6440-2UC21-5BA1) using the signal of an inline rotary encoder (Danaher Controls model HS351024E4447). The motor and the speed reducer are suspended by an aluminium device known as a "cradle" (parts shaded in grey in Fig. 2a). The cradle is connected at both ends to the calibration rig frame with bearings. The cradle and the equipment it supports are free to rotate around the centreline of the motor. On the driving shaft side, the cradle bearing (Kaydon Reali-Slim™ model JB035GP0) has an internal diameter of 88.9 mm which leaves enough space for the 28.6 mm diameter output shaft to link the gear box to the device being calibrated. To transmit torque to the equipment being tested, the cradle rotation is held by a locking arm that connects the cradle to the calibration rig frame. An S-beam load cell (Sensortronics model 60001) is used to measure the locking force.

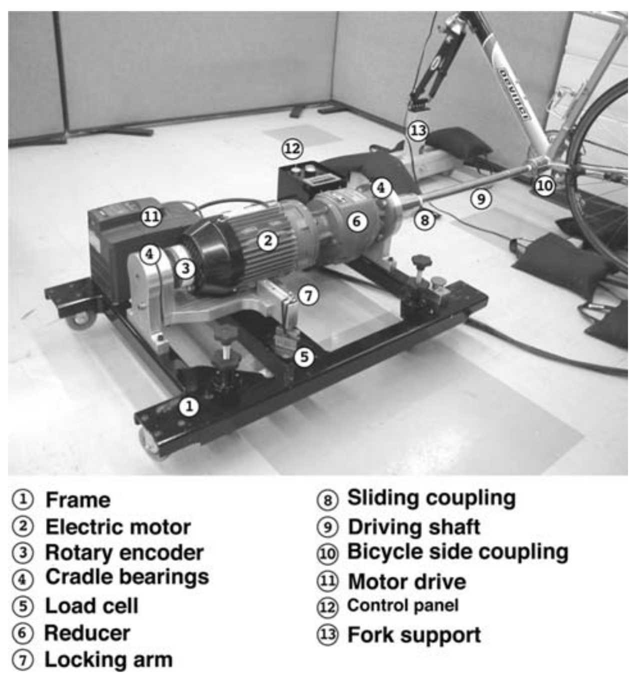

Fig. 1 Calibration rig connected to a bicycle for the calibration of a home trainer (not shown in this picture)

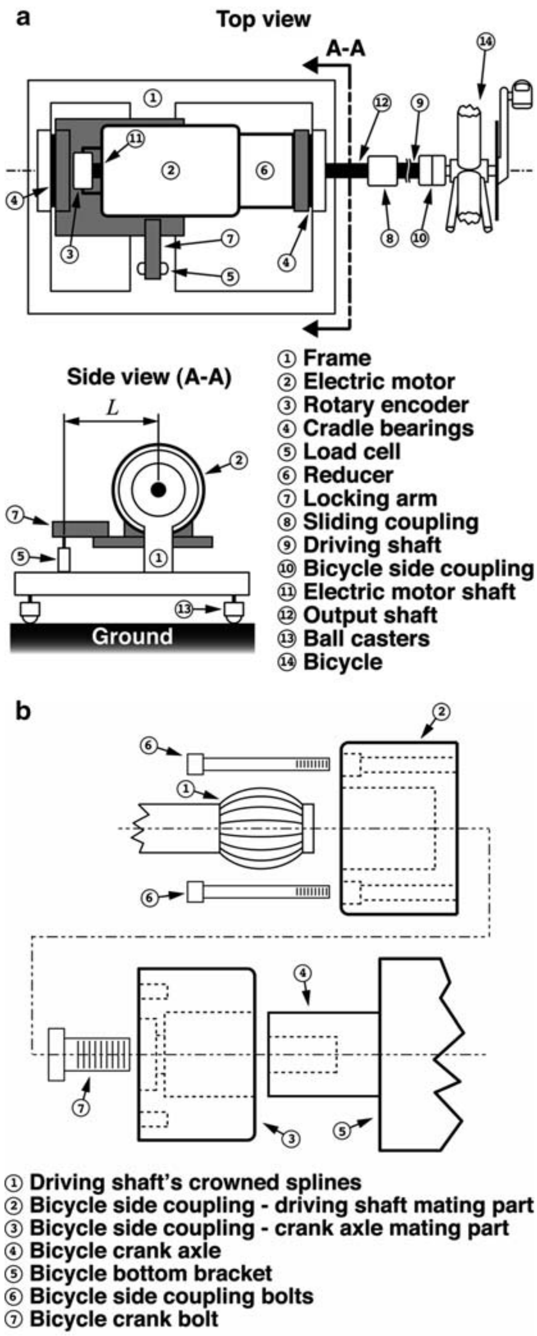

Fig. 2 **a** Diagram of the calibration rig. The distance L represents the lever arm length. **b** Detailed diagram of the bicycle side coupling (exploded view shown)

The power P (W) transmitted to the crank axle is related in a linear fashion to the transmitted torque C (N m) and angular velocity ω (rad s^{-1}).

$$P = C\omega \qquad (1)$$

Pre-selected pedalling cadences within the range of 80–130 rev min^{-1} are available. The rotary encoder installed on the motor shaft provides the appropriate electric signal to the drive controller to accurately control the motor's angular velocity. The torque C is linearly related to the locking force F (N) measured by the load cell, and to the lever arm length L (m) which is a constant value.

$$C = FL \qquad (2)$$

Ease of use is one of the main characteristics of the proposed calibration system and the alignment between the bicycle and the calibration rig is a critical element. To facilitate alignment, a driving shaft with crowned splines at both ends links the calibration rig to the crank axle. The crowned splines facilitate the connection process of the shaft by taking misalignment up to 5°. A sliding coupling on the reducer output shaft side can be shifted back and forth along the shaft. In the process of installing the driving shaft, the coupling slides over the driving shaft end splines to make the connection. This allows the shaft to be easily installed or removed without having to move the bicycle or the calibration rig. The coupling between the driving shaft and the crank axle can be changed to adapt to the different crank axle models (Octalink™, ISIS™, square-hole design, etc.). A detailed diagram of this coupling is shown in Fig. 2b. Two sets of wheels are installed on the calibration rig. Four rubber wheels allow the calibration rig to be moved around. The second set is made of three 32 mm (diameter) ball casters mounted at the end of three vertical threaded rods that are installed in a triangle pattern on the calibration rig structure. The ball casters allow the calibration rig to move easily in any direction for easy alignment and height adjustment to the equipment undergoing calibration. When the ball casters are in contact with the ground, the transportation wheels do not touch the ground and vice versa. When the calibration rig is adequately positioned, thin U-shaped pieces of rubber are forced around the ball casters to keep the calibration rig stationary during the tests.

The control panel (Fig. 3) is used to input settings for the calibration ring. It uses commercially available components. Starting with a general purpose instrument enclosure (Hammond Manufacturing model 1401A), it

Fig. 3 Control panel of the calibration rig

consists of a start/stop switch, master on and off pushbuttons, a selector knob to select the pedalling cadence (80–130 rev min^{-1} with 10 rev min^{-1} increments) and a Tracker 200 Data Track Input Indicator to display the force level. The master on and off pushbuttons control the electrical power supply of the calibration rig. The start/stop switch and pedalling cadence selector are connected to the electronic drive to control the electric motor operation. The load cell is connected to the input indicator.

2.2 Accuracy of the calibration rig

To measure the power delivered by the calibration rig, three independent quantities must be measured: the locking force F, the angular velocity ω and the lever arm length L. For the force measurement, the selected load cell has a full scale rating of ±667 N. According to the transducer specifications, the force reading uncertainty is 0.03% (0.2 N) of the Full Scale Output (FSO), the non-linearity is 0.03% FSO with an hysteresis of 0.02% FSO. The nominal sensor sensitivity of 3.238 mV/V FSO has been checked experimentally and was found to be within manufacturer specifications.

The angular velocity is measured by a Sealed Hollow Shaft encoder with a 1024 Pulse Per Revolution based on a two-channel quadrature capability. Using an external magnetic pulse sensor connected to a data acquisition system, the velocity precision has been checked experimentally at various loads and at all calibration rig preselected velocity settings. A magnet fixed to the output shaft provided a sharp one-pulse-per-revolution signal. The data acquisition sampling frequency was set at 1,000 Hz. The time history of the measured pulse train was used to calculate the average rotational velocity of the shaft for ten consecutive revolutions. The maximum discrepancy between the available speed settings (80, 90, 100, 110, 120, 130 rev min^{-1}) and the direct measured rotation speed values was found to be less than ±0.1%.

The lever arm length L and its dimension accuracy were established using the experimental setup shown in Fig. 4. An aluminium extension piece was temporarily connected at the end of the locking arm. This allowed a known external calibrated moment to be imposed on the calibration rig. A calibrated mass m (6.0002 ± 0.0005 kg) was used to apply a known force F_m. The mass was hung sequentially at positions 1 and 2 along the extension piece and the respective forces F_1 and F_2 were measured using the calibration rig load cell. Two small holes drilled on top of the extension piece were used to accurately position the weight. The two holes were drilled using a milling machine to maximise the accuracy of the holes separation distance a (600 ± 0.03 mm). The following equation allows L to be calculated:

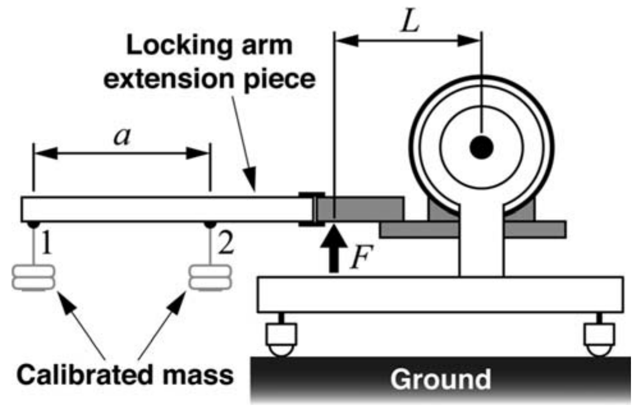

Fig. 4 Experimental setup to estimate the lever arm length L. Points 1 and 2 correspond to the location where the calibrated mass is sequentially hung. a and F represent the distance between points 1 and 2, and the locking force, respectively

$$L = aF_m/(F_1 - F_2) \quad (3)$$

It was determined that $L = 181 \pm 1$ mm. This simple procedure offers two important advantages. First, it is not necessary to locate the force line of action relative the output shaft axis, or to know the mass of the extension piece. Only the weight F_m and the distance a between the force line of action at positions 1 and 2 must be known. Second, because a ratio of forces measured with the same load cell is used to calculate the power $[P = C\omega = FL\omega = aF_mF\omega/(F_1 - F_2)]$, power measurement does not require the use of the load cell sensitivity value. Only an accurate linear behaviour of the load cell is required.

It was necessary to determine if the splined connection of the driving shaft had an influence on measurement and more specifically, if there was any energy dissipation in the connection. A special driving shaft was designed and built to be rigidly bolted on the couplings at both ends. Tests were conducted to compare the power measured by the calibration rig when using either the bolted connection or the splined connection. The bolted connection imposes a zero degree misalignment and no energy loss is possible. All the other elements of the test setup were identical and a load of 300 W was imposed and kept constant for all the tests. In this experiment, the maximum allowable misalignment by the crowned splines was set to maximise energy loss. For both configurations, no measurable difference could be established because the difference between the measured force F_m in both conditions was within the measurement uncertainty of ±1 N.

The accuracy of a measuring system must be established by taking into account all sources of uncertainty. The most dominant element that influences the uncertainty level in the described system is the time variation character of the measured force. When a bicycle ergometer or home trainer is tested, inherent cyclic load variations are generated by several sources such as an out-of-round rear tyre or wheel or the deformation of the chainrings. Noise is also introduced by chain impacts on the gears and by other moving parts. Time averaging is an efficient way to improve the accuracy of the mean of a signal showing cyclic variations. Averaging over a long time period could be used to estimate the average force in a steady state condition. In this application, it is nevertheless important to maintain an efficient calibration procedure. The averaging time must not be too long and a compromise must be established. A rolling average filter with a time average set at 20 s was selected on the Tracker 200 Force indicator. A statistical analysis of the variation of the force F_m established the force uncertainty at ±1 N at 95% (confidence level). Taking into account the relative uncertainty of all the measured parameters, the maximum power uncertainty delivered by the calibration rig for a nominal power level range of 50–600 W is ±0.9%.

2.3 Calibration procedure

Specialised computer software was developed to assist non-expert users during the calibration procedure. The software runs on a Windows PC that is not connected to the calibration rig. This software was written in Visual Basic and provides dialogue boxes, including the one shown in Fig. 5, for setting calibration parameters and entering force data. It also interpolates the stored data to produce calibration charts. The choice of calibration parameters depends on the calibration mode. Two modes of calibration are possible with this software: a batch mode and a single reading mode.

In the batch mode, users must enter the pedalling cadence range (80–130 rev min^{-1} with 10 rev min^{-1} increments) and workload levels (from 50 to 600 W with 50 W increments) for which the equipment is to be tested. For home trainers, gear sizes used during calibration must also be entered because the load they impose is proportional to the angular velocity of the small cylinder in contact with the rear wheel of the bicycle. The batch mode generates calibration charts and is best suited to the calibration of bicycle ergometers and home trainers when used in their power-controlled mode in which they are expected to maintain fixed workloads regardless of the pedalling cadence or gear size.

The single reading mode is not intended to generate a calibration chart and no calibration parameter needs to be set. This mode allows for calibration of equipment at a given single pedalling cadence and workload level combination. It is well suited for the calibration of power monitoring devices such as the SRM powermeter or the PowerTap hub. In this case, the workload should be provided by a braking system such as a home trainer.

Before connecting the calibration rig to the equipment for testing, a self-check for accuracy of the calibration rig is performed to confirm that the force measurement system is functioning properly. To do this, a calibrated mass is placed at a specific location on the locking arm and the force reading is compared to a reference value. Once the calibration rig has been connected to the equipment to be tested, the software is first used to select the calibration mode and parameters.

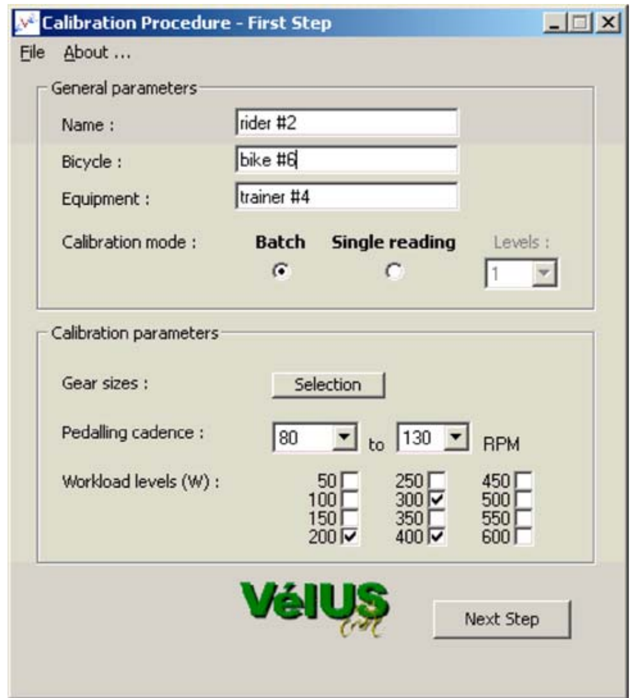

Fig. 5 Calibration software main input dialogue box used for the definition of general and calibration parameters

The calibration rig is then started and the warm-up period begins. The warm-up pedalling cadence and workload level are set to the first pedalling cadence and workload level for which the equipment is to be tested. In the batch mode, these settings are provided by the software and correspond to the lower limit of the pedalling cadence range and the lowest workload level selected. The warm-up period is considered completed when the value of the force reading remains constant within ±1 N for at least 1 min.

The next step is the collection of the calibration data. In the batch mode, the software guides the user by providing the pedalling cadence and the workload level (and gear size for home trainers) and allows the corresponding force reading to be entered. Using all the measured data, calibration charts are generated by the software and then printed.

3 Results

To illustrate how the calibration rig is typically used, the calibration charts of two home trainers of different brands have been obtained and the power output measurement accuracy of two bicycle power monitoring devices has been determined.

3.1 Home trainers

Figure 6a and b show sample calibration charts for a Tacx Flow Ergotrainer (Technische Industrie Tacx BV, the Netherlands) and a Computrainer Pro Basic (RaceMate Inc, USA), respectively. These home trainers use an electromagnetic brake to apply resistance to the rear of a bicycle and the brake operation is controlled by a multi-purpose controller attached to the bicycle's handlebar. Both units were set in their power-controlled mode and were tested using the calibration system batch mode. The same bicycle (Mikado d'Iberville) and tyre (IRC Redstorm 700 × 25 C at 7.5 bar, gear size: 46 × 15) were used throughout the tests. The manufacturer's self-calibration procedure was carried out on both apparatuses. The calibration was done for six workload settings ranging from 100 to 600 W by 100 W increments and at a pedalling cadence ranging from 80 to 130 rev min^{-1} by 10 rev min^{-1} increments.

3.2 Bicycle power monitoring devices

Table 1 shows sample accuracy check results for two bicycle power output measuring devices: a SRM Pro crankset (Schoberer Rad Meßtechnik SRM GmbH, Germany) and a PowerTap Pro hub (Saris Cycling Group, USA). The SRM and the PowerTap devices are strain gauge transducers that measure the torque generated by the cyclist at the crank and at the rear hub, respectively. The power is calculated using this torque measurement and the crank angular velocity or the rear wheel angular velocity provided by a dedicated sensor. The SRM and the PowerTap units were both installed and tested simultaneously on the same bicycle (Argon 18 Radon, tyre: Michelin Pro Race 700 × 23C at 8 bar, gear size: 53 × 16). A Tacx Speedmatic home trainer was used to impose the workload only. The workload level range (330–607 W) was covered by increasing the pedalling cadence from 80 to 130 rev min^{-1} by 10 rev min^{-1} increments.

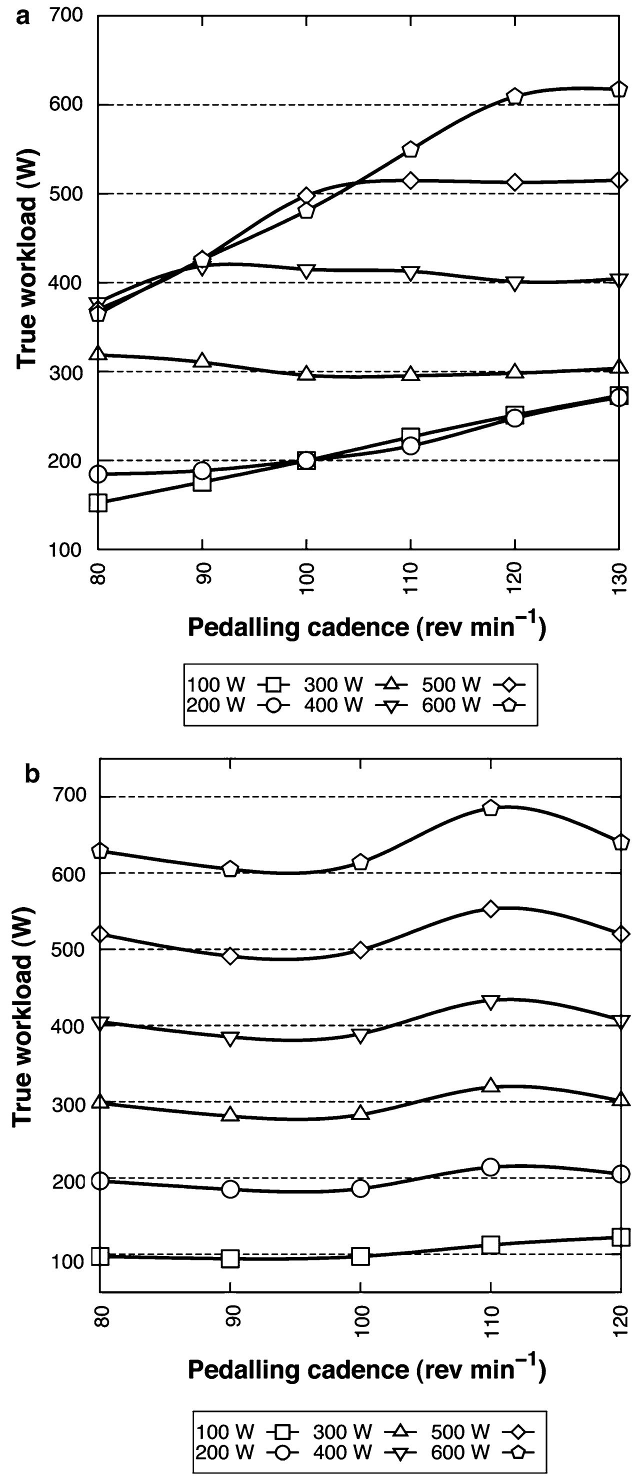

Fig. 6 Calibration charts of two electromagnetically brake home trainers (**a** Tacx Flow Ergotrainer; **b** Computrainer Pro Basic) for six workload settings (power-controlled mode) ranging from 100 to 600 W by 100 W increments

4 Discussion

The results illustrated in Fig. 6a and b show that the Tacx and the Computrainer units behave differently. Ideally, a home trainer when used in its power-controlled mode, would impose for each workload settings, a constant and accurate braking power regardless of the pedalling cadence or gear size. One would then expect to have horizontal lines on calibration chart. As shown in Fig. 6a for the 400–600 W workload settings, the Tacx Flow cannot impose the expected workload until the pedalling cadence reaches a high enough value. This behaviour suggests that the brake

Table 1 Accuracy check results for the SRM and the PowerTap units

Run	Power measurement (W)		
	Calibration system	SRM	PowerTap
1	330	330	319
2	389	391	380
3	444	445	434
4	498	497	486
5	557	554	543
6	607	602	591

torque reaches its maximum value for some pedalling cadence and workload setting combination and that the true workload can therefore only be varied by increasing the pedalling cadence. The Tacx unit also cannot impose a true workload lower than 150 W at any pedalling cadence. Above 100 rev min^{-1}, the minimum true workload is 200 W. The 100 W curve suggests that the brake torque is at its minimum at this workload level setting since the true workload is linearly related to the pedalling cadence ($R^2 = 0.9994$). The Computrainer unit does not show any workload output limitations within the tested range. When considering only the points for which the brake torque is within its functioning range, the mean absolute error for the Tacx Flow is 10.2 W (SD = 6.1 W). For the Computrainer unit, this figure is 16.8 W (SD = 17.6 W). This higher mean value is due to the Computrainer behaviour around a pedalling cadence of 110 rev min^{-1}. At this pedalling cadence, a maximum discrepancy of 85 W is noted at the 600 W workload setting. For home trainers, it is interesting to note that the calibration also depends on the bike gear ratio and the pedalling cadence used, because these two parameters influence the angular velocity of the home trainers' roller in contact with the rear wheel tyre.

For the SRM powermeter and the PowertTap hub (data in Table 1), the mean error was −0.14% (SD = 0.49%) and −2.6% (SD = 0.40%), respectively. The SRM produced a range of percent error scores from −0.82% at 607 W to 0.51% at 389 W. The PowerTap produced a range of error scores from −3.33% at 330 W to −2.25% at 444 W. The results for the six runs are consistent with the SRM manufacturer's specification accuracy of ±2%. The PowerTap was outside the manufacturer's reported accuracy (±1.5%) for the six runs. According to Gardner et al. [3], the PowerTap displays lower values than the SRM because transmission losses in the chain and sprocket drive mechanism are not taken into account. The SRM instrumented crank uses the calibration slope indicated on the back cover of the instrument. One could use the calibration rig to obtain power readings to verify or re-evaluate the slope. A full description of this procedure goes beyond the scope of this paper.

During the calibration of bicycle ergometers or home trainers, the influence of brake temperature on brake torque should be taken into account. Clark and Greenleaf [1] have reported large errors during calibration as a result of brake temperature increase. Gardner et al. [3] also reported that both the SRM powermeter and PowerTap hub are temperature-sensitive. This project did not include the objective of studying the effect of temperature on the workload output of bicycle ergometers and home trainers or on power monitoring systems measurements. Force readings were recorded only when the systems were in a steady state condition; that is, when the calibration rig's force reading reached a stable value for at least 1 min.

In this paper, "calibration" has been used in its broadest sense. However, when the equipment being tested cannot be calibrated by users, either mechanically, electronically or via an adjustable setting parameter in the instrument software, the calibration charts generated by the calibration software are used as correction charts. In the case of a home trainer for example, these correction charts could be used to select the equipment-indicated workload in order to obtain the desired true workload. In situations where calibration charts are used as correction charts, it is assumed that the equipment is used at a steady pedal cadence.

When using the calibration charts, it is important that the calibration conditions reproduce the normal operating conditions as closely as possible. For home trainers, for example, because the workload is imposed at the rear wheel, all the energy losses in the bottom bracket bearings, chain, sprocket drive mechanism, rear wheel bearings, rear wheel air drag and tyre are accounted for in the calibration chart. These losses are specific to the bicycle used during calibration. Therefore, the same bicycle and settings should be used during calibration as during normal operation of the home trainer.

The use of a cradle mounted on bearings is a key feature that improves both the durability and accuracy of the calibration rig. Because the cradle bearings essentially provide pin boundary conditions but do not rotate, they will not wear out and will consistently maintain adequate boundary conditions. More importantly, they eliminate the need to estimate power consumption. One important advantage of the proposed reaction torque calibration rig is that it is not necessary to take into account any internal energy loss of the system associated with the motor bearings, the reduction gearbox, or the motor cooling fan. The choice of aluminium for the frame and the cradle and the use of an aluminium electric motor have helped to reduce the mass of the calibration rig to 75 kg. The main objective in reducing the mass was to facilitate the transportation of the calibration system by car.

The proposed calibration system has been used for over a year at the Canadian National Cycling Training Centre in

Bromont (Canada) by non-expert personnel who attended an hour-long training session on the use of the calibration rig and software. The set-up and warm-up period is typically 15–30 min long and each force reading usually takes less than 2 min.

5 Conclusions

Periodic calibration or accuracy checks are an essential step when carrying out measurements. For power measurement in cycling, two obstacles that hinder more frequent use of calibration systems are the length of time and the expertise required to operate them. We therefore developed a new calibration system to overcome these limitations. The system can be used to calibrate bicycle ergometers, home trainers as well as bicycle power monitoring devices. It consists of a calibration rig and specialised calibration software to guide the user during the calibration procedure and to produce calibration charts. The integration of several key features at all levels allowed us to obtain an accurate system while guaranteeing easy and efficient use by non-expert personnel. To demonstrate the potential of the system, we generated calibration charts for two home trainers and carried out an accuracy check on two bicycle power monitoring devices. Power discrepancies were noted. We also demonstrated that the proposed calibration system is an effective tool in characterising the behaviour of home trainers.

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