Crank-based Cycling Powermeter – Construction and Validation

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Abstract: We describe a single-sided crank-based cycling powermeter intended for mountainbike (MTB) use. The device is based on a printed circuit board (PCB) supplied by its manufacturer, but its assembly differs from the official instructions. The main difference is that the strain gauges are applied on the inside of the crank spindle. This was achieved by using a dedicated clamp that ensures easy application and precise positioning of both of the strain gauges relative to each other and to the other parts of the assembly as well. Other aspects of our design include mainly space considerations and waterproofing. The validation step was performed by comparing power readings to a consumer-grade indoor trainer under various riding conditions. The most important outcomes are, therefore, the design of the clamp used for gluing the strain gauges and the potential in teaching mechanics using a complex project.

Keywords: bicycle powermeter; design; validation.

1 Introduction

Powermeters are nowadays ubiquitous in almost any form of competitive cycling, their use ranging from track, triathlon and road racing to BMX, MTB and ultra-endurance events. The use of powermeters has been proven to bring many benefits, some being evident, such as objective effort quantification, better pacing or improving pedaling dynamics, while some being not so obvious, such as optimizing diet or aerodynamics [1, 2].

The working principle of different products may differ, but the most common one is to measure torque or force applied to a structural member of the drivetrain (such as pedal, crank arm, crank spindle, chainring spider or rear hub) and the corresponding angular velocity. The torque/force is usually measured by means of strain gauges. The design of a powermeter might provide measurement of total power output or the power output of each leg separately or the power output of one leg only (so-called single-sided powermeter), in which case it is assumed that both legs deliver the same amount of power.

Our choice of the working principle and design was driven by the availability of a ready-made electronic module provided by its manufacturer and its low price. It is a single-sided powermeter built into the inside of a hollow crank spindle. Our paper therefore describes the installation of the supplied module into a suitable crankset, its calibration and validation of power readings.

2 Design, manufacture, and assembly

We obtained the SG53 powermeter module and strain gauges, see Fig. 1, from their manufacturer, Sensitivus Gauge, within their project “DIY power meter”. The website of the project [3] provides basic instructions for the build and calibration of the powermeter. The suggested procedure, however, includes placing the strain gauges to the outside of the crank spindle and routing the wires through a $2\,\mathrm{mm}$ hole drilled in the spindle. We rejected this design to avoid premature failure of the crankset in the harsh conditions of MTB racing (both in terms of loading and environment). Instead, we decided to place the strain gauges on the inside surface of the spindle, which results in all the components being sealed inside and no additional weakening of the structure. This approach, however, brings the following problems:

- to bond the strain gauges reliably from inside the crank spindle (inner diameter $20\,\mathrm{mm}$);
- to position the two strain gauges relative to each other with sufficient precision.

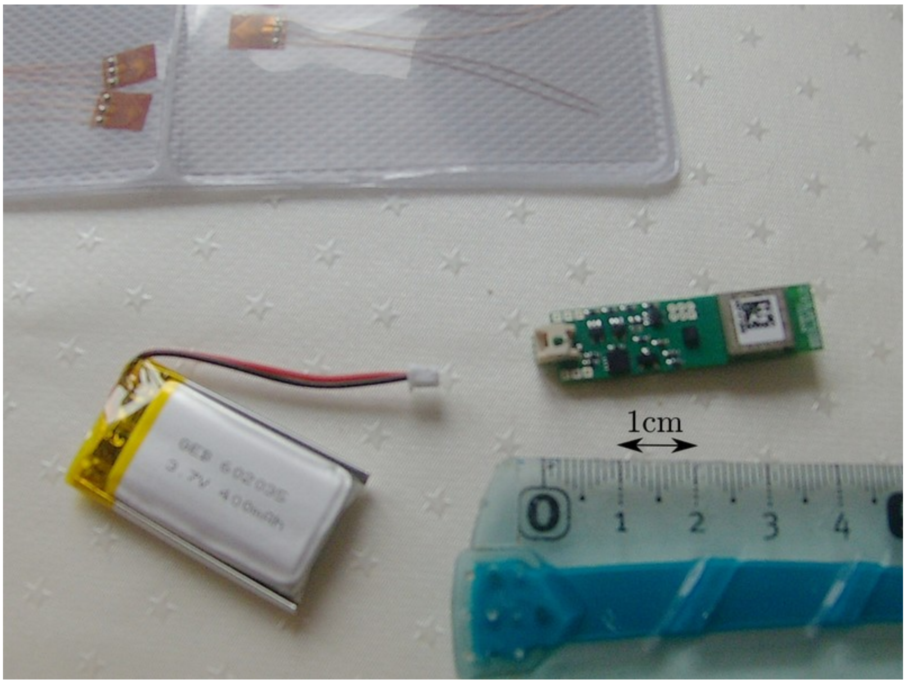

Fig. 1: The parts supplied by the electronics manufacturer: strain gauges (top), lithium-ion battery (left), SG53 powermeter module (right). Scale shown for size comparison.

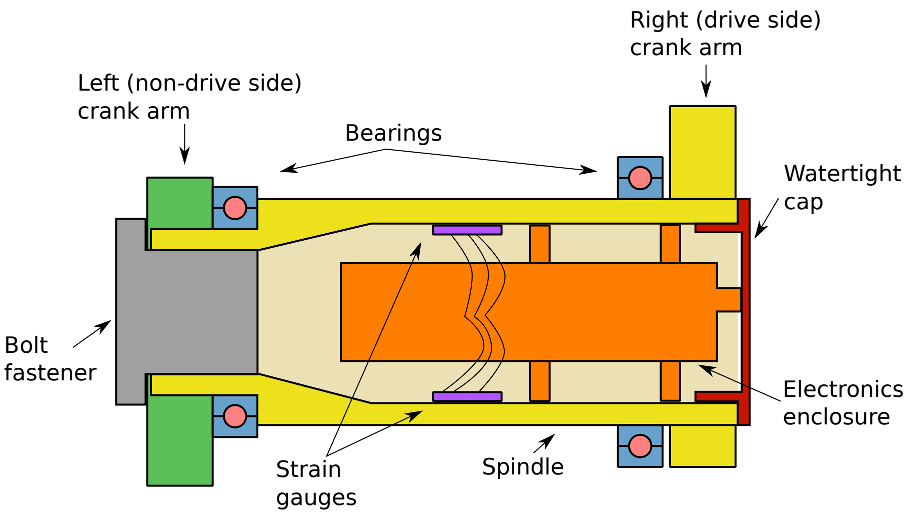

Fig. 2: Schematic depiction of the Sram GXP bottom bracket with the powermeter assembly.

Other challenges are common with the official design:

- to design the parts in a way that they can be assembled together;
- waterproofing;
- placing the antenna so that the wireless signal is not blocked.

The powermeter was intended to be built into a basic Sram S1000 crankset that uses the Sram GXP bottom bracket. The interface between bottom bracket bearings and the spindle is of 24 mm diameter on the drive side and 22 mm on the non-drive side (see Fig. 2). Both the radial and the axial loads are transmitted to the non-drive side bearing whereas only radial loads are transferred to the drive-side bearing. The inner diameter of the hollow spindle is 20 mm on the drive-side opening and decreases toward the threaded non-drive side end.

Fig. 2 provides a schematic depiction of the assembly. The main parts are the strain gauges, wiring, an enclosure for the electronics, and a watertight cap. The exact shapes of the enclosure and the cap were developed using 3D printed prototypes and a dummy copy of the spindle. The dummy copy was used for dry-fitting the parts together and testing the assembly process. See Fig. 3 for an overview of the prototypes.

The only resource that the authors could find regarding placement of strain gauges inside a hole uses an inflatable membrane [4]. We propose an alternative approach, in which proper placement of the strain gauges is

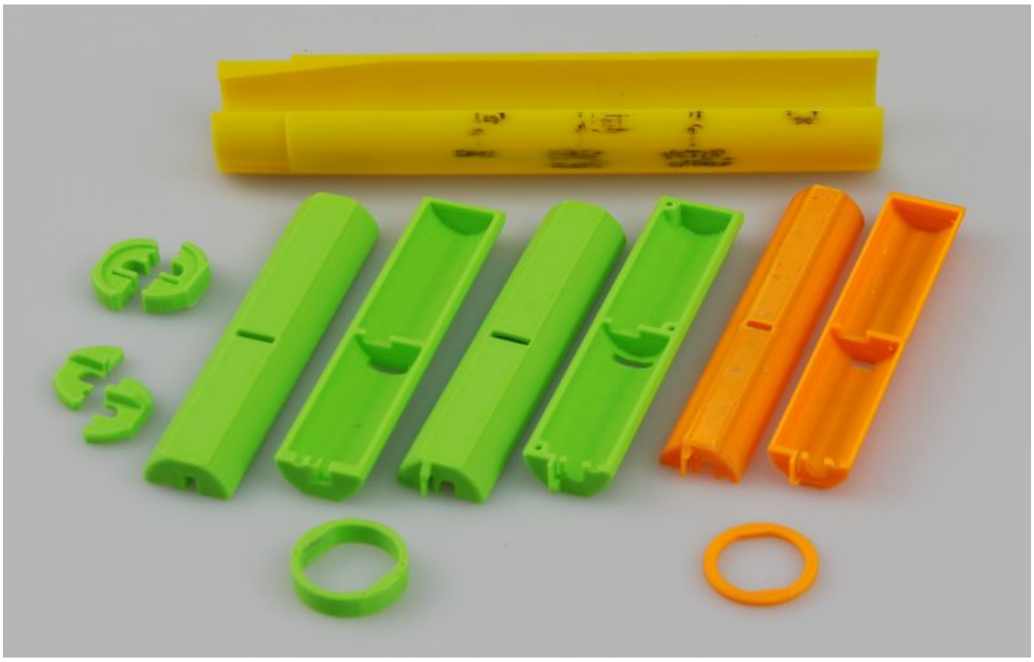

Fig. 3: Prototypes of the enclosure, end cap, and the dummy copy of the spindle.

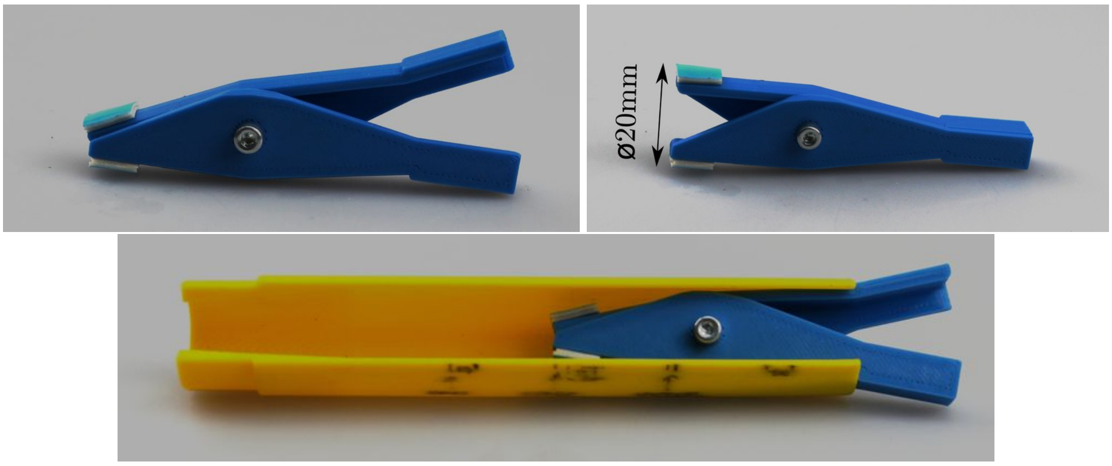

Fig. 4: Clamp for gluing the strain gauges.

achieved by using the custom-made clamp shown in Fig. 4. Our clamp is, again, 3D printed with a small amount of soft padding at the ends that ensure uniform pressure distribution onto the strain gauges during the gluing process. The strain gauges were bonded to the padding by a small amount of double sided tape, which released easily after the strain gauges bonded to the spindle so that the clamp might have been removed. Moreover, the surface of the padding was covered by a plastic foil that did not stick to the strain gauges glue, thereby reducing the chances of damaging the strain gauges while removing the clamp. The shape of the clamp enables to fix the outer end until the glue cures and also fits the spindle in a way that ensures that the strain gauges are placed in the exact desired distance from the outer end of the spindle.

3 Calibration and validation

The build of the powermeter is finished by its calibration, i.e. setting the internal parameters of its firmware in a way that the power readings are accurate. Next is the validation by comparing its power readings to another calibrated and trusted powermeter. These steps are described in detail in the following two paragraphs.

3.1 Calibration

Calibration was performed according to the official recommendations, i.e.:

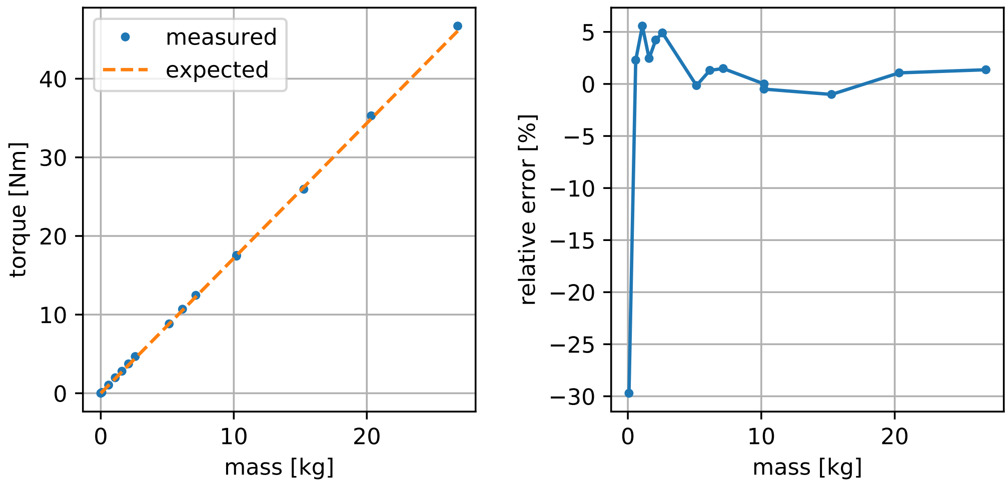

Fig. 5: Comparison of measured and expected torque values with different calibration weights.

1. Zero the powermeter with no load on the pedals using the developers mobile app.
2. Put the cranks into horizontal position.
3. Hang a known weight, $m \in \langle 10, 20 \rangle$ kg, to the left crank arm.
4. Read the value of torque, M_{measured}, in the mobile app.
5. Compare that value to the expected value of torque

$$M_{\text{expected}} = m\,g\,l\ , \tag{1}$$

   where $g = 9.81\,\text{N/kg}$ is the gravity of Earth and $l = 0.175\,\text{m}$ is the length of the crank arm.
6. Set the calibration parameter in the app to $M_{\text{expected}}/M_{\text{measured}}$.

We calibrated the powermeter using $m = 10.12\,\text{kg}$ and then compared the torque readings at different weights, see Fig. 5. The results show linear behavior and acceptable relative error of less than $2\,\%$ for $m > 5\,\text{kg}$. With heavier weights ($m > 10\,\text{kg}$), however, it became increasingly difficult to perform the measurement due to balancing, positioning issues and noticeable deformation of the bicycle frame. For this reason, it is good practice to use a dedicated test stand for powermeter calibration.

3.2 Validation

The Wahoo Kickr Core indoor trainer was used for comparison of the power readings. It is mounted in place of the rear wheel to the bicycle (see Fig. 6), uses a $5.44\,\text{kg}$ flywheel, an electromagnetic break, and estimates pedaling cadence from slight changes in power output. Its claimed accuracy is $\pm 2\,\%$ and maximum measurable power $1800\,\text{W}$.

The obvious consequences of this testing setup are:

- Pedaling asymmetry results in errors in power readings due to the tested powermeter being single-sided.
- Friction losses in the drivetrain may cause a slight difference in power readings.

The first issue is an inherent property of the design of the tested powermeter and cannot be eliminated. Friction losses were reduced by cleaning the drivetrain and lubricating the chain (using a paraffin wax bath) prior to testing.

Since the head-unit (cycling computer) can only be paired with one powermeter at a time, a mobile app was used to record the data from the indoor trainer over the Bluetooth Low Energy protocol. Each recording was then saved in a `.fit` file and read using the `fitparse` python library [5].

Fig. 7 shows the recorded quantities, namely power and pedaling cadence. The ride starts with a 10-minute warm-up, which includes easy riding around $100\,\text{W}$, variations in pedaling cadence ($50 - 110\,\text{RPM}$), single legged pedaling, and a short sprint ($> 700\,\text{W}$). The single legged efforts are clearly recognizable by: (1) the

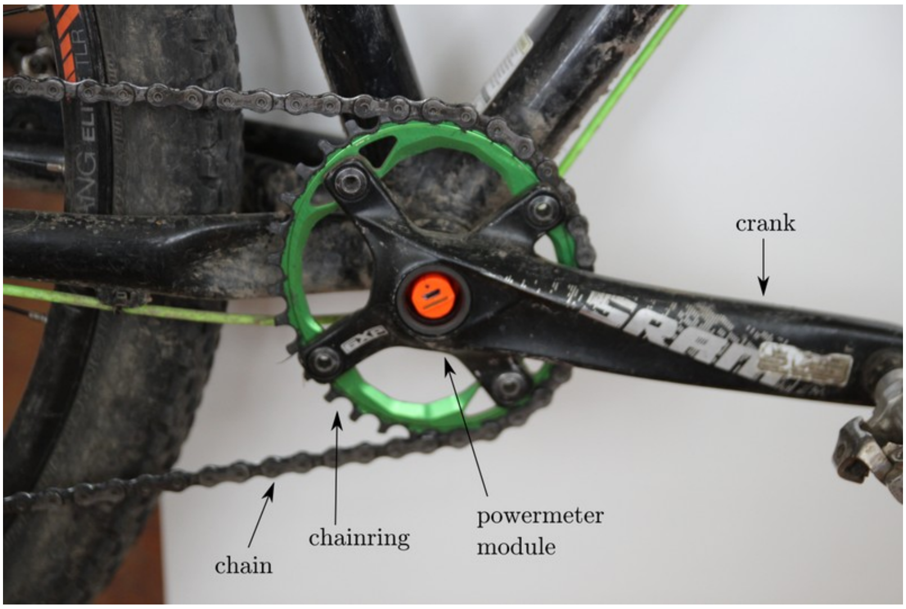

Fig. 6: The bicycle and indoor trainer as used for validation (top). Close-up on the installed powermeter with the watertight end cap removed (bottom).

pedaling cadence estimated by the indoor trainer being dropped to about one half and (2) the power readings of the tested powermeter being dropped to zero during the right leg effort and being increased twice during the left leg effort. There is also a discrepancy at high cadence, say above $100\,\mathrm{RPM}$. This might have to do with altered pedaling dynamics or asymmetry and will be investigated further.

After a short pause, the test continues by several $30\,\mathrm{s}$-intervals at intended constant power output from $50\,\mathrm{W}$ to $350\,\mathrm{W}$, spaced by $50\,\mathrm{W}$. Data from this part of the test are shown in Fig. 8. The power readings show good agreement in general. One noticeable aspect is that it becomes more difficult to control the power output at harder efforts. This is mostly caused by insufficient training of the rider, but increasing fatigue and changing gears also play a role.

The final stage of the test consists of easy riding at $100\,\mathrm{W}$ with a short maximum effort sprint in the middle. Data from the sprint are shown in Fig. 9 and display very good agreement considering the achieved power output of more than $800\,\mathrm{W}$. The slight disagreement is most probably caused by altered pedaling dynamics due to the effort, by different data collection on the two recording devices, and by the cadence calculation together with power averaging.

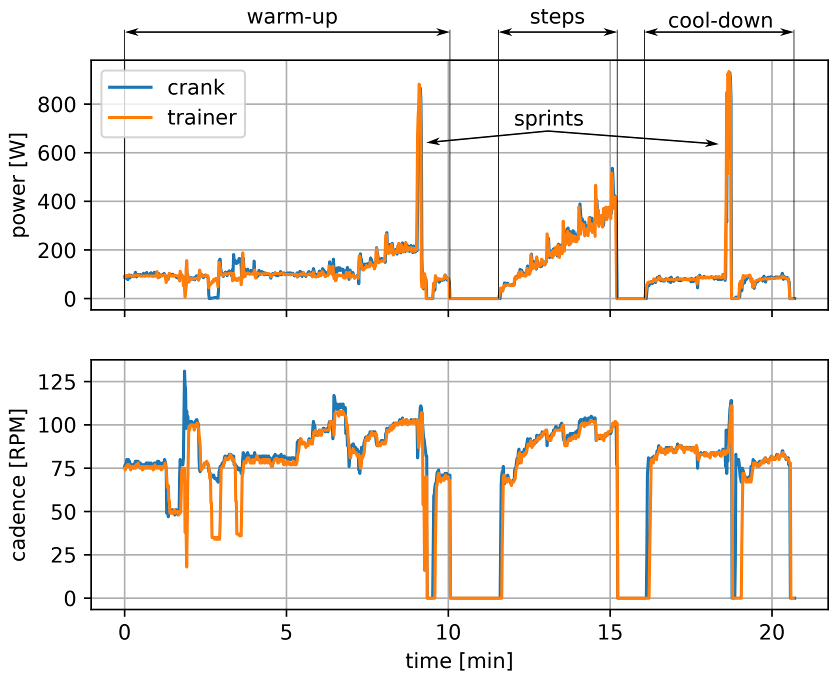

Fig. 7: Data from the validation ride.

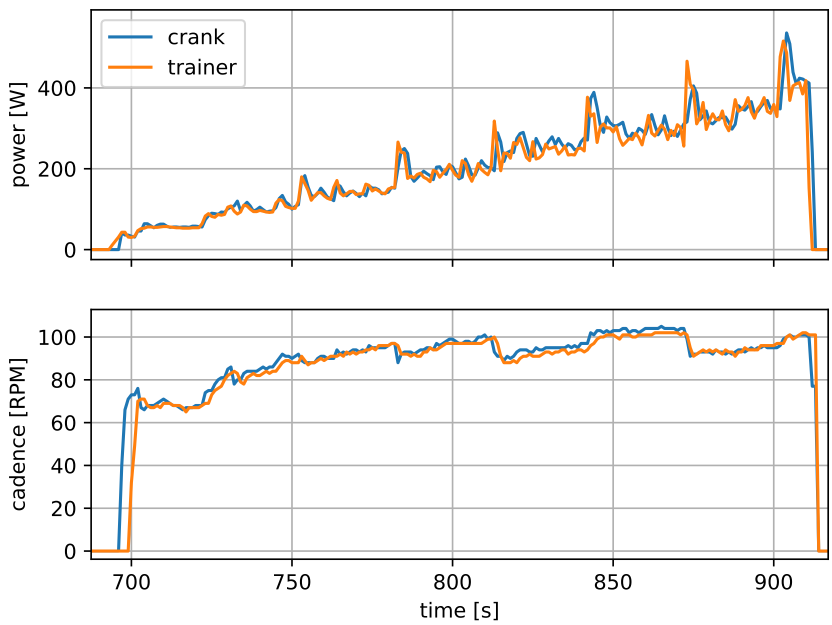

Fig. 8: Data from the validation ride – steps at constant power.

4 Summary

The cycling powermeter build described in this work resulted into several valuable outcomes. The first one is the development and testing of the described method of placing a set of strain gauges inside a deep narrow tube using a dedicated clamp. Another valuable result is the design of a waterproof end cap that was 3D printed from a flexible material. This approach proved superior to the use of o-rings in the context of spatial constraints of the assembly and mechanical durability. Our solution is, however, not fully tested yet as long-term degradation of the 3D printed material in outdoor conditions might prove crucial.

Another point worth emphasizing is the benefit of similar projects for one's technical skills and understand-

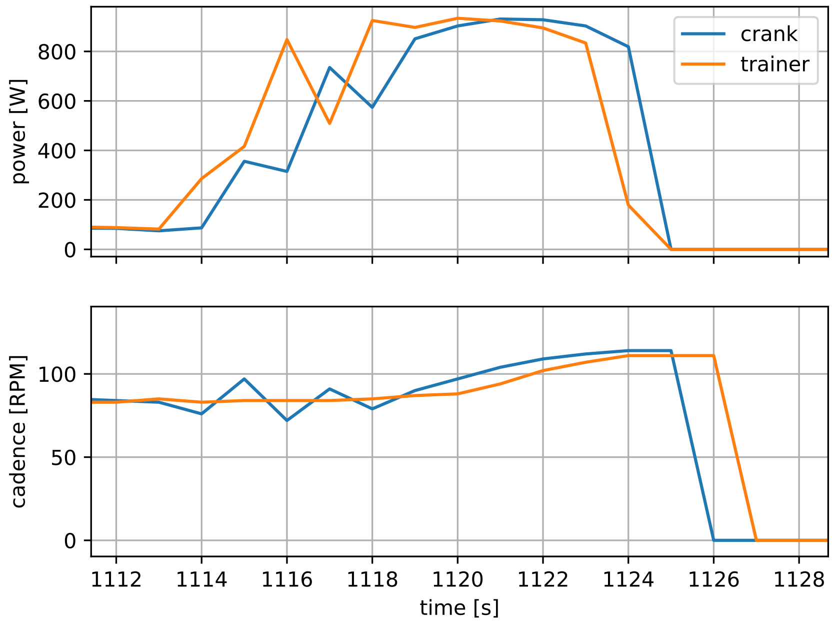

Fig. 9: Data from the validation ride – maximum effort sprint.

ing of mechanics. The key property is the complexity of the project, which means that the student needs to combine knowledge and skills from different areas – e.g. 3D drawing, industrial design, electronics, theory – and even gain some completely new ones. The difficulty of the project may be tailored in order to match the skills of the students and expected gains, e.g. by using (or not using) ready-made components (such as the SG53 module in our case) or by specific guidance (or the lack of it) regarding design or manufacture of the parts. Validation is an important step of the project in order to evaluate the design choices and other aspects of the prototype.

Future development and use of these results may include:

- use of similar clamps for strain gauges placement in production;
- changes in firmware in order to fully analyze the collected data, including accelerometer, pedaling smoothness, and torque effectiveness data;
- use of similar projects in teaching experimental mechanics and industrial design;
- development of own PCB module, possibly extending it for independent measurement of power output of both legs;
- use of power measurement in biomechanics for testing the hypotheses of muscle activation or the mechanisms of muscle fatigue;
- use of power measurement in sports education and medicine.

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