Development and evaluation of a novel power meter device in cycling: a proof of concept study

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Abstract

A power meter device was developed by placing a PolyPower force sensor in between two aluminium plates. The device was mounted in between a cycling shoe and cleat, and was compared to a Monark ergometer. Continuous tests of workloads at 50, 100, 150 and 200 W and an incremental test revealed that the power meter device underestimated the power output. This was most likely due to the power meter device´s inability to measure forces in the anterior-posterior axis and the force sensor´s slow recovery rate.

Keywords: cycling, power meter, power output

Introduction

Intensity load monitoring in cycling has changed in recent years. Previously, cyclists were limited to heart rate and speed monitoring, but the introduction of power meters, which measure the power output, has improved the analysis of cycling performance. Power output measurements are not affected by wind, gradient of the road or natural biological variation, and as a result, power meters have become an important training tool in cycling (7).

Traditionally, power has been measured at the crankset, which is also the employed method by the most used power meter device, SRM. Systems also exists that measures the amount of torque generated by the pedaling of the cyclist at the hub of the rear wheel (PowerTap) and the pedals (Garmin Vector). The common denominator of these power meter systems is that they measure torque by use of strain gauges. Pedal force measurement devices made for use in the laboratory usually employs strain gauges as well (2, 6, 8, 9, 11, 12) but systems using sensors based on piezoelectricity (4), the Hall effect (13) and piezoresistive effect (3) have also been developed.

Danfoss PolyPower A/S has recently developed a Dielectric Electroactive Polymer called PolyPower, which has the potential to be used as a force sensor as well. When deformed, the PolyPower charges its electrical properties and provides an output that is proportional to the magnitude of deformation (5). The PolyPower sensor has a number of advantages over other load cells because it is small, lightweight, durable and easy to install.

The ease of installation enables the sensor to be used in connections that were not previously thought of. The aforementioned power meters are all mounted on the bicycle. If a user has several bicycles and wants to measure the power output on more than one, it would require either several expensive power meters or to switch one power meter from bike to bike, which can be time consuming and requires a certain amount of technical expertise. Therefore, the aim of this study was to develop and produce a prototype power meter device, containing a PolyPower force sensor, which could be mounted in the connection between a cycling shoe and pedal, and test its accuracy.

Method and materials

Development and production of the power meter device

Based on the aim of the study, it was decided to develop a device that could be mounted between a cycling shoe and cleat. This novel approach creates a wearable power meter that is attached to the cyclist rather than the bike.

A design was proposed, where the PolyPower sensor was placed in between two plates shaped as an isosceles trapezoid with screw holes that match those of a Shimano SM-SH11 cleat (Shimano Inc., Sakai, Japan). The proposed design enables the plates and sensor to act as the connecting link between cycling shoe and cleat.

Two plates of aluminium (aluminium alloy 6060) with a length of 6.5 cm, a maximal width of 8 cm and a minimal width of 4 cm were used. Three holes with a diameter of 0.5 cm were drilled through the two plates in order for the cleat to be connected to the shoe. Force applied from pedaling will push the plates into the sensor, which will undergo deformation and record a change in capacitance that can be converted to force.

Because of the slightly bended cycling shoe, the machine bolts that connected the cleat and power meter device to the shoe, were at an oblique angle and created friction with the plates. To avoid this, the holes in the plates were increased to a diameter of 1 cm. The machine bolts had a length of 4 cm and the upper part was without screw thread to avoid friction between plates and bolts. To further reduce friction, the bolts were lubricated with Super Lube® Multi-Purpose Grease (Super Lube, New York, USA).

As some riders pull the pedal upwards during cycling (10), the device should have a mechanism which provides the device the ability to measure force when pulled instead of pushed. This was made by inserting rubber washers between the head of the bolts and plate. The bolts were then tightened to create a pretension in the sensor. When pulling the pedal the top plate could then be pulled upwards relieving the sensor of tension.

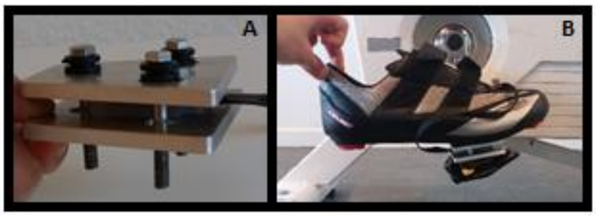

Figure 1: Pictures of the power meter device. The device was mounted in between a cycling shoe and cleat (B).

The total weight of the power meter device was 181 g with a height of approximately 1.8 cm.

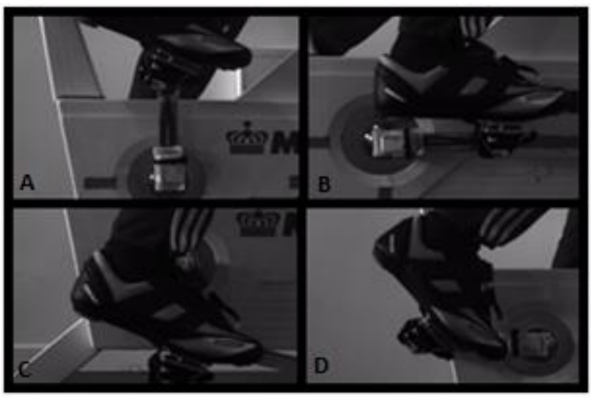

Figure 2: The crank at angles of 0° (A), 90° (B), 180° (C), 270° (D).

Data processing

Due to the construction of the power meter device, the sensor is able to record the normal or vertical force that is applied from pedaling. It is however, only the force vector acting perpendicular to the crank that produce propelling power on the bicycle. This force is called effective force and if crank angle and pedal angle is known, it can be computed using basic trigonometry. The angle of the crank and pedal was obtained using two inertial measurement units (IMU) (Shimmer3, Shimmer, Dublin, Ireland). The IMUs´ built-in accelerometer and gyroscope recorded and sampled angular rotational speed and acceleration using specific software (LabVIEW, National Instruments, Austin, USA) at 512 Hz. One IMU was mounted at the center of rotation of the crank and the other at the center of rotation of the pedal. Angular speed and acceleration was converted to angle using trigonometry. The measurement of crank and pedal angle by the IMUs was validated by comparing a pedaling trial with a high-speed camera (Basler AG, Ahrensburg, Germany) recording at 350 fps. The IMUs and the force sensor transmitted data to a computer using Bluetooth.

The pedal torque (PT) was calculated as follows:

$$PT = F_{eff} \cdot L \tag{1}$$

where F_{eff} is effective force and L is the distance in meters from the crank spindle to the pedal spindle (0.170 m).

The angular velocity of the rotating crank (ω) expressed in radians per second (rad·s^{-1}) was obtained from the pedaling cadence (C), expressed in revolutions per minute (RPM), recorded by the ergometer:

$$\omega = \frac{C \cdot 2 \cdot \pi}{60} \tag{2}$$

The power output (P), expressed in Watts (W) as the mean value for every two seconds, was calculated as follows:

$$P = PT * \ \omega \tag{3}$$

The pretension mechanism, which allows the device to measure pulling forces, is constructed using rubber washers. When the device is pulled, the rubber washers are compressed, which requires a certain amount of force. The amount of force that is used to compress the rubber washers can be computed by performing a compression test of respectively the rubber washers and force sensor in order to find the correlation between force and deformation. Consequently, because the sensor measures the change in capacitance, which can be converted to force, the deformation of the sensor is known at all times. Because of the way the device is constructed, the change in deformation of the rubber washers is the opposite of the sensor´s. When the deformation of the rubber washers are known, the force needed to compress the rubber washers is also known. Therefore, compression tests of the rubber washers and the force sensor were performed and measurements of force and deformation were collected using a Zwick Z100/TL3S materials testing machine (Zwick GmbH & Co. KG, Germany)

Validation of power meter device

To test the validity and reliability of the power meter device, it was compared to a Monark 839 stationary ergometer (Monark Exercise AB, Vansbro, Sweden) with clipless pedals (Shimano 105 PD-R540 SPD-SL, Shimano Inc, Sakai, Japan). The Monark 839 is a mechanically weighted and braked ergometer, where the work performed on the ergometer is the product of the weight lifted times the numbers of revolutions. The Monark 839 is not able to store data but can be set to a constant workload or an incremental protocol, where the workload is constantly increasing with time. The power meter device was calibrated using a Zwick Z100/TL3S materials testing machine (Zwick

GmbH & Co. KG, Germany) and mounted in between a cycling shoe and cleat, and attached to the right pedal. Force measured by the PolyPower sensor was recorded and sampled at 50 Hz using sensor software (Wireless Sensor Controller, Danfoss PolyPower A/S, Nordborg, Denmark). The power meter device was pretensioned with a force of 38 N. This test setup only measures the power output of the right leg, which is doubled to estimate the total power output. This method is similar to the commercially available system Stages and could produce erroneous results if the cyclist is injured or asymmetric in pedaling style.

A recreational male cyclist (age: 25 years old, height: 1.79 m, body mass: 76 kg, weekly cycling training: 4 hours) volunteered as subject for this study. Prior to testing and after having been explained the nature and the purpose of the study, the subject gave written informed consent. The subject performed a 15 min. self-chosen warm up session, which also acted as habituation to the test setup. Prior to the warm up, the seat height was adjusted to fit the subject.

After the warm up, the Monark ergometer was calibrated according to the instructions of the manufacturer.

Following a 10 minute break, the subject performed the experimental protocol in a laboratory at room temperature. The protocol consisted of:

- Sub-maximal 2-min continuous tests with constant workloads of 50 W, 100 W, 150 W and 200 W at 60 RPM. 2 min break between workloads. This protocol was repeated three times.
- Sub-maximal 2-min continuous tests with constant workloads of 50 W, 100 W, 150 W and 200 W at 90 RPM. 2 min break between workloads. This protocol was repeated three times.
- An incremental test of an increasing workload of 2 $W \cdot s^{-1}$ from 50-200 W at 60 RPM.

Statistical and data analysis

Power for the initial 10 s was discarded for each trial to allow the subject to reach the desired cadence and power output on the ergometer. Data from the power meter device, Monark ergometer and IMUs were analysed using MatLab (R2014b, The MathWorks, Mass., USA). Data from the power meter device (second-order Butterworth) and IMUs (fourth-order Chebyshev Type II) was low-pass filtered. Correlation between the power meter device and the Monark ergometer was investigated using a Pearson´s correlation coefficient (r) in Statistical Package for the Social Sciences (SPSS v22.0, SPSS Inc., Chicago, USA). A significant difference was set at $p < 0.05$. Data was presented as mean values ± SD.

Results

At the 2-min continuous tests of constant workloads of 50 W, the power meter device measured an average power of 48.8 ± 5.0 W (60 RPM) and 40.0 ± 10.2 W (90 RPM) (table 1). This corresponds to a difference of 2.4% (60 RPM) and 20.0% (90 RPM) respectively. At constant workloads of 100 W, the average power measured by the power meter device was 88.6 ± 14.4 W (60 RPM) and 17.5 ± 4.3 W (90 RPM), which corresponds to a difference of 11.4% (60 RPM) and 82.5% (90 RPM). The power meter device measured at constant workloads of 150 W an average power of 138.5 ± 8.1 W (60 RPM) and 37.4 ± 2.5 W (90 RPM). This corresponds to a difference of 7.7% (60 RPM) and 75.1% (90 RPM). At continuous tests of 200 W, the power meter device measured an average power of 156.9 ± 16.3 W (60 RPM) and 74.9 ± 14.3 W (RPM), which corresponds to a difference of 21.6% (60 RPM) and 62.5% (90 RPM).

Power output during different workloads

Monark 839E (W)	Power meter device 60RPM (W)	Power meter device 90RPM (W)
50	48.8 ± 5.0	40.0 ± 10.2
100	88.6 ± 14.4	17.5 ± 4.3
150	138.5 ± 8.1	37.4 ± 2.5
200	156.9 ± 16.3	74.9 ± 14.3

Table 1: The power output of the power meter device at 60 RPM and 90 RPM during the 2-min continuous tests at different workloads compared to the Monark ergometer.

The difference in force profiles from 10-second random samples of the continuous tests at 100 W can be seen in fig. 3 at 60 RPM (A) and 90 RPM (B), respectively.

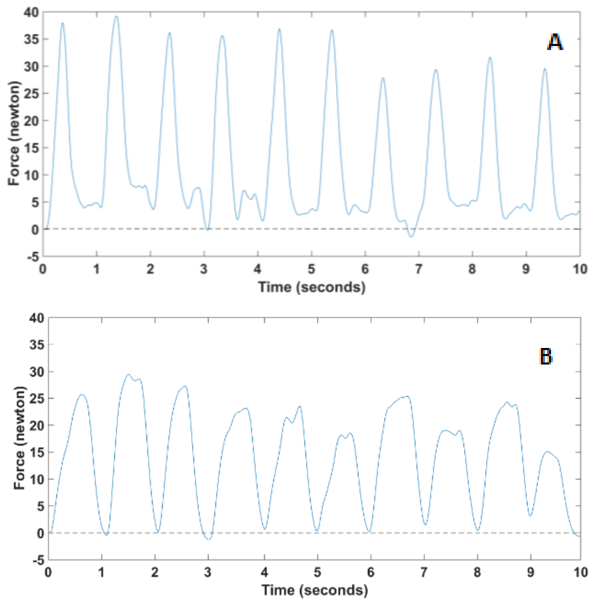

*Figure 3: Force profiles of random 10-second samples during a 100 W trial at 60 RPM (**A**) and 90 RPM (**B**).*

Fig. 4 shows the force profile at 100 W of a single revolution at 60 RPM (A) and 90 RPM (B), respectively.

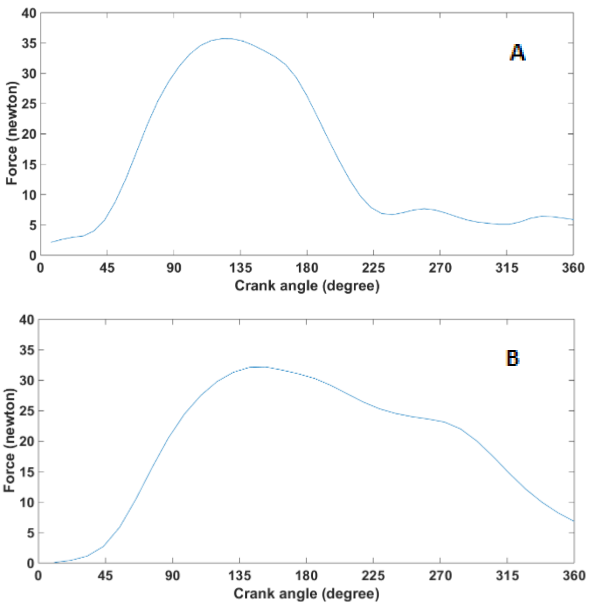

*Figure 4: Force profile of a complete revolution during a 100 W trial at 60 RPM (**A**) and 90 RPM (**B**).*

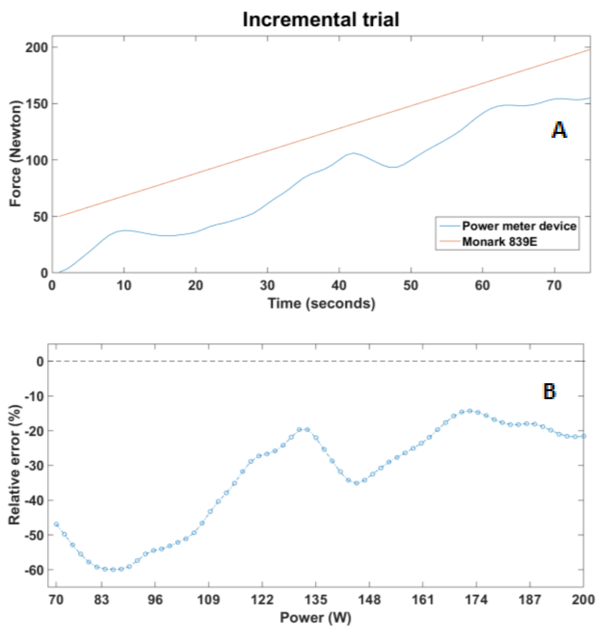

*Figure 5: (**A**): Graphical overview of the power output of the power meter device (blue) and the Monark ergometer (red) during the incremental test. (**B**): Plot of the relative error of the power meter device during the incremental test compared to the Monark ergometer*

There was a strong correlation between the power meter device and the Monark Ergometer during the incremental test (r = 0.98, $p < 0.01$).

Fig. 5 (B) displays the relative error of the power meter device compared to the Monark ergometer during the incremental test. The average relative error was 33.2% in the incremental test.

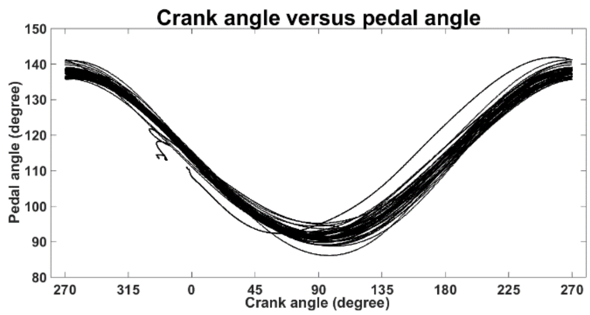

Figure 6: Graphical overview of the crank angle and pedal angle during a workload of 100 W at 60 RPM. 0° crank angle is at upper dead spot and 180 ° is at lower dead spot. 90° pedal angle is when the pedal is perpendicular to the ground. When the pedal is tilted forwards, the angle is > 90°.

Fig. 6 displays the crank angle and pedal angle in relation to each other during a continuous test of 100 W.

Discussion

The aim of this project was to develop and manufacture a power meter device that could be mounted in between a cycling shoe and cleat using a PolyPower force sensor, and test its accuracy. This was accomplished by placing the sensor in between two plates capable of compressing the sensor when a force was applied.

When compared to a Monark ergometer during continuous tests of workloads from 50 – 200 W, the power meter device severely underestimated the power output. On average, the power meter device underestimated the power out by 10.8% when the cyclist was riding at a cadence of 60 RPM and 60.1% when the cyclist was riding at a cadence of 90 RPM. This is well above the maximal satisfactory measurement error set by Abbiss et al. at 2.5% (1). The only trial that could be deemed satisfactory was the workload of 50 W at 60 RPM (2.4% inaccuracy). The underestimation of power output may partly be explained by the power meter device´s lack of ability to measure shear forces. Studies have shown the anterior-posterior force component to produce a significant magnitude of propulsive force when cycling with clipless pedals (3).

The power meter device displayed a very large measurement error during the continuous tests at different workloads at a cadence of 90 RPM. When looking at fig. 3 and fig. 4, different force profiles are clearly observable between 60 RPM and 90 RPM. At 60 RPM, the force profile displays a large force applied during the first half of a revolution, while a smaller amount of force is applied during the second half of the revolution. This force profile is similar to what has been found by others (3). The force profile of 90 RPM, on the other hand, displays a large force applied during both the first and second half of the revolution. While the force applied during the first half contributes to propulsion of the bicycle, force applied during the second half opposes propulsion unless the pedals are pulled upwards. This would help explain the very low power output measured by the power meter device during 90 RPM.

It was observed that the recovery rate of the PolyPower sensor was very slow. As a result, when the sensor was loaded and unloaded, it did not return to its non-deformed state immediately but exhibited a delay. At the faster cadence of 90 RPM, the sensor may not have enough time to properly undeform. A faster recovery rate could be achieved by reducing the sensor´s volume of surrounding silicone layer and increasing the stiffness of the material. Conversely, if the stiffness is too high, the precision of the sensor might be reduced. A faster recovery rate would be a major improvement of the power meter device. Another solution could be to employ another load cell as the force sensor, e.g. strain gauges.

Even though the force measurement did not seem to be accurate, pedal kinematics assessment using IMUs was validated and as a result, the pedaling technique of the subject can be analyzed. It was observed that the subject rarely pulled the pedal upwards during the second half of the revolution, which could provide propulsion of the bicycle. Furthermore, the pedal was always tilted forwards except at a crank angle of ≈ 90° at which the pedal was perpendicular to the ground. Especially during the first quarter of the revolution, it would be favourable for the subject to slightly tip the pedal backwards to make it more parallel to the crank. Cyclists might benefit from using training tools that are capable of assessing the pedaling effectiveness.

The power meter device that was developed in this study is unique in the sense that it is a wearable power meter that is attached to the cyclist rather than the bicycle. Commercially available power meters require to be mounted on the rear hub, crank or pedals for example. If a user has several bicycles and wants to measure power output on more than one, it would require either several expensive power meters or to switch the power meter from one bicycle to another, which can be time consuming and requires a certain amount of technical expertise. A wearable power meter does not present the same challenges for the user as it follows the cyclist and not the bicycle.

Conclusion

A power meter device was developed and mounted in between a cycling shoe and cleat, acting as a wearable power meter for cycling. When compared to a Monark ergometer, the power meter device severely underestimated the power output, especially at a high cadence. This was most likely due to an inability to measure anterior-posterior forces and a slow recovery rate of the force sensor. Based on pedal kinematics assessment, it was observed that the subject could improve pedaling technique. Consequently, it might be beneficial for cyclists to use training tools that are capable of assessing the pedaling effectiveness.

Acknowledgements

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2015

Project notes

Development and evaluation of a novel power meter device in cycling: a proof of concept study

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Gr. 1047

Sports Technology

Master´s Thesis

Aalborg Universitet

Table of contents

Introduction to the project notes

The project notes are a more detailed description of the study and the theory behind it. The following parts does not necessarily follow a connecting thread.

Introduction

In 1817 Karl Drais invented the velocipede, which was the first machine to bear a resemblance to the modern bicycle. The cyclist had to kick himself forward on the velocipede by pushing off the ground. Pedals were later attached to the rear wheel and eventually the front wheel. To increase the speed, the circumference of the front wheel was enlarged and the popular high wheeler was created. In 1879 the first bike with a chain drive was invented. This bike made it easier to mount and get off the bike and so it was named the safety bike. The basic construction of the safety bike is similar to the modern bikes, which have added gear, air filled tires and pedals attached near the crank as well (43).

Propulsion of a bike occurs when the cyclist is exerting energy on the pedals. This energy passes through a sequence of mechanical components (called the "powertrain") before it drives the rear tire against the road surface. When pressing down on the pedals, the crank axle and the chain rings rotate. A chain is then transferring the force to the hub of the rear wheel, which rotates on its axle, transmitting torque out through the spokes to rotate the wheel and drive the tire against the road surface. The pedals usually consist of a spindle attached to the crank arm, and a pedal body, which is in direct contact with the shoe of the cyclist. The pedal body is often made out of aluminium, steel or plastic. Some pedals require a cycling shoe with attached cleats, which acts as a locking mechanism to keep the shoe attached to the pedal. As a consequence, the cyclist is able to pull the pedal upwards in addition to providing downward force. A pedal cycle consist of four phases or positions called downstroke phase, upstroke phase and two dead spots. The two dead spots are located at the top and bottom of the pedal cycle, when the crank arm is in a vertical position at a 0° and 180° crank angle. These two positions are called dead spots as only a small amount of the force applied to the pedals contribute to propulsion. Downstroke phase is from the moment the pedal leaves the top dead spot to the bottom dead spot or the crank arm´s range of rotation from 0° to 180°. The majority of the force that generates propulsion is in this phase. The upstroke phase is the remaining 180° from the bottom dead spot to the top dead spot and is characterized by the lifting of the cyclist´s leg (23).

Previously, cyclists were limited to analysing their performance and training using heart rate monitors and speedometers. These tools can be misleading as the speed for example varies according to the wind, draft and gradient of the road. Furthermore, factors other than the physical condition can contribute to variation in heart rate such as natural biological variation, dehydration, temperature and altitude (22).

A new training tool was invented in 1986 by Ulrich Schoberer. Schoberer Rad Messtechnik (SRM) made it possible to objectively measure the performance of the riders (21). At the beginning, the SRM system was expensive and primarily used by professional riders and in test laboratories. In the course of time, the price has been reduced and amateur riders use the system nowadays as well. The SRM system was the first of its kind; a power meter but the market is growing with the introduction of manufacturers such as PowerTap, Quarg, Stages, Garmin and Look Keo Power.

An effective training program is based on a suitable balance between training duration, frequency and intensity. Duration and frequency can easily be monitored but intensity is more difficult. As previously mentioned, using speed and heart rate as estimates for physical activity can be misleading. Power is advantageous as a measurement of training intensity as power measure the amount of energy transferred to the pedals by the cyclist per unit time. When measuring power, the cyclist can be certain that if the intensity is doubled, it is because the cyclist is transferring twice as much energy to the pedals per unit time, and not because of a change in wind direction or gradient of the road (10).

Usually, power meters have a number of strain gauges attached to the crank of the bike in order to measure the torque created as a consequence of the rider´s pedaling. However, power meters mounted on the hub of the rear wheel and the pedals also exist. Mounting the power meter at the pedals instead of at the crank or the hub is beneficial because the power meter is switched between bikes more easily and quicker, which is useful if one has several bikes. In addition, a pedal-based power meter is able to display the balance of the rider, which is the power in percentage produced by the left and right leg. This is useful during rehabilitation as progress is easily and quickly monitored. When measuring the pedal forces, the technique of the bike rider can be analysed using the ´Index of effectiveness´, which is the ratio between effective force and the total force applied to the pedal (7). Research (8, 24, 25) has shown that skilled cyclists exhibit a higher pedal force efficiency. In addition, measurement of pedal forces can help manufacturers develop even better and more durable pedals for bikes. The use of pedal force has mostly been used in biomechanical studies in which knowledge of pedal forces is combined with electromyography to show a connection between muscle activity and force production (7).

As previously mentioned, the majority of power meters measure deformation using strain gauges. If the deformation occur in a material with a known elasticity, it is possible to convert the deformation to force. Strain gauges however, are not the only load cells capable of measuring power. Danfoss PolyPower has developed a thin polymer, PolyPower, that uses Dielectric Electro Active Polymer technology to act as a sensor. If the sensor is stretched, the electrical properties are changed and the sensor exhibits an output that is proportional to the amount of stretch (14). The PolyPower sensor is small, light and durable. The sensor has Bluetooth Low Energy communication, which enables the sensor to be easily found by most modern computers, smartphones and bike computers.

In the present project a device with a PolyPower sensor acting as a force gauge is developed and manufactured. The device can be mounted between a cycling shoe and pedal, and its power output measurement is compared to a stationary ergometer.

Background of project

Power meters

Power meters for bicycles are best described as devices capable of measuring the power output of the cyclist. There is an increasing demand in technology able to quantify the performance of cyclists, and monitoring of this has very much changed from measurement of heart rate to power as the latter is not effected by temperature or blood circulation (6). Most power meters cooperate with a small computer mounted on the handlebar. The bike computer can display information such as instant, maximal and average power output, and usually heart rate, speed, distance and time as well. Power meters are especially useful during interval training compared to heart rate monitors. During short intervals, measurement of heart rate can prove to be inconclusive as the heart rate raises steadily until steady state is reached. A power meter however, instantly displays the output of the cyclist. A power meter is also ideal for pacing to avoid racing beyond the physiological limits of the bike rider.

Power meters are often small and expensive because they have to fulfill a long list of demands from the consumer. Primarily, the quality of data has to be satisfying. The power meter should also be accurate and consistent in all types of weather, and very durable. In addition, installation, use and access to data should be easy and the product´s availability and service support should be taken into account.

Power

Power is the rate of doing work and can be defined as energy produced per unit time. Power is measured in the unit Watt in cycling. Watt is defined as joule per second and can be described as the amount of work performed in a given time period:

$$P = \frac{\Delta W}{\Delta t} \tag{1}$$

P is the average power, ΔW is the change in work and Δt is the change in time. Work is performed when a force acts over a distance or displacement and equation (1) can as a result be replaced by:

$$P = \frac{\Delta(F \cdot d)}{\Delta t} \tag{2}$$

F is force and d is distance. Distance divided by time is equal to speed and equation (2) can as a result be replaced by:

$$P = F \cdot v \tag{3}$$

v is speed. A bicycle consists of many rotating parts such as the pedals, the crank, the chain and the hubs. In rotating systems, power is the product of the torque and the angular velocity:

$$P = \tau \cdot \omega \tag{4}$$

τ is torque and ω is angular velocity. Torque is the product of the magnitude of the force and the lever arm, and is measured in the unit N·m (40). Angular velocity can, among others, be measured in the units radians per second or revolutions per minute, also called the cadence in cycling when the revolutions of the crank per minute is measured. Consequently, in order to compute the power output of a cyclist, a torque needs to be measured and multiplied by an angular velocity. By looking at equation (4) it can be observed that if a torque is applied without a resulting motion, the power output will be equal to 0 W. This is evidenced by the fact that power meters should display a power output of 0 W when the cyclist is standing on the pedals or hitting a bump on the road without the crank rotating, even though a force is applied to the pedals.

Cycling is connected to power. The higher a power output, the faster the bike will move forward if aerodynamic forces are ignored. The power output is used to overcome drivetrain friction, inertia forces associated with acceleration of the bike, gravitational forces in climbing, tire rolling resistance and aerodynamic drag (10). A simplified functional equation of motion for cycling can be written as:

$$P_{cyc} = P_{dt} + m \cdot V \cdot A_{cyc} + W \cdot V \cdot \sin(ArctanG) + W \cdot V \cdot C_{rr_1} \cdot \cos(ArctanG) + N \cdot C_{rr_2} \cdot V^2 + \frac{1}{2}\rho \cdot C_d \cdot A \cdot V(V + V_w)^2 \tag{5}$$

P_{cyc} is the power output produced by the rider, P_{dt} is the amount of power used to overcome drivetrain friction, m is the mass of rider and bike, V is bicycle velocity, A_{cyc} is instantaneous acceleration or deceleration of rider/bike system, W is the weight of rider and bike, G is the gradient, C_{rr_1} is the coefficient of static rolling resistance, N is the number of wheels, C_{rr_2} is the coefficient of dynamic rolling resistance, ρ is the air density, C_d is the coefficient of aerodynamic drag, A is the frontal surface area of the rider and bike and V_w is the velocity of the headwind or tailwind (10).

Commercially available power meters

Schoberer Rad Messtechnik (SRM) hit the market in the late 1980´s and since then there has been a growing number of power meters. All of them share the ability to measure or estimate the cyclist´s power output. How they do it and where they are mounted on the bike differs from manufacturer to manufacturer. It will be described in the following part how and where some of the most popular manufacturers measure power on bikes.

SRM is a crankset and the most popular power meter on the market. SRM measures the cyclist´s power output by using strain gauges placed in between the bottom bracket and chainrings (4). The SRM comes in three models with either 4, 8 or 20 strain gauges. When extended or compressed the strain gauges exhibits a change in electric resistance, which can be converted to a voltage signal. Whenever an external load is applied to the pedals, a small deformation will occur in the crank. By strategically placing the strain gauges, this deformation can be converted to voltage. If the relationship between the applied load and voltage is known, the deformation can be converted into torque. Subsequently, SRM measures the angular velocity in radians per second by multiplying the cadence with 2 and π, and divide by 60 (42). The cadence is measured using reed switches (6). SRM is considered the golden standard for power meters in cycling. Several studies have shown SRM to be valid and reliable and even better than stationary ergometers (19, 28, 32, 34). A possible problem with the SRM and other power meters is that an average angular velocity is computed after every revolution. Sudden changes in power out has therefore shown to have a certain margin of error (1). If the power meter is to be switched to another bike, it requires that the entire crankset is replaced. SRM adds approximately 100-200 g to the bike.

Powertap measures power in a similar way to SRM by using strain gauges. One major difference is that PowerTap has 8 strain gauges mounted to the hub of the rear wheel instead of at the crank. By using strain gauges, SRM and PowerTap suffers from the same sources of error such as temperature compensation and placement of strain gauges. PowerTap measures the torque at the hub of the rear wheel. Consequently, the angular velocity must be measured at the same spot, and the cadence cannot be used. Instead, the angular velocity is measured using a magnet in the spindle and a reed switch in the body of the hub. Studies have shown, that PowerTap underestimates power compared to SRM (4). This is most likely due to the fact that PowerTap measures power in the hub of the rear wheel, whereas SRM measures power at the crank. Mechanical energy is transferred from the chainrings to the rear wheel through the chain and gear but the friction between these will consume a portion of this energy (10). Studies (4) have shown that the friction is responsible for a loss of 2-4% and if this loss is accounted for, PowerTap and SRM measure with the same precision. Because PowerTap measures power at the hub of the rear wheel, the power meter is attached to the rear wheel, and if it is to be switched between bikes, the rear wheel should be replaced. PowerTap adds approximately 300 g to the bike.

Stages is a small container glued to the left crank arm. As Stages is only mounted to the left crank arm, it is restricted to measuring power produced by the left leg of the cyclist. The power is afterwards doubled because of the assumption that there exists a symmetry between left and right leg power output. However, studies have shown that injured athletes exhibit asymmetry of up to 400 % between the injured and non-injured leg (26, 33). Stages measures the torque by using strain gauges, and angular velocity by using accelerometers to compute the cadence. The power meter can be switched between bikes by replacing the crank arm, and it adds approximately 20 g to the bike.

Garmin Vector is a power meter that measures the torque in the pedal spindle by using 8 strain gauges in each pedal. Vector is basically two independent power meters in each pedal. A container is attached to each pedal and one of them sends the force output to the other, which sends the total information to the bike computer. Garmin Vector measures the angular velocity by using integrated accelerometers in the containers to measure cadence. As strain gauges are mounted in both pedal spindles, the Garmin Vector is capable of displaying the power output from the left and right pedal independently. Garmin Vector pedals can only be attached to Look Keo cleats, and in order to switch the power meter between bikes, the pedals have to be replaced and installed correctly. The power meter adds approximately 100 g to the bike.

The above power meters are all examples of mobile ergometers. In the scientific world stationary ergometer bikes are often used, which measure power by having the cyclist overcome some kind of friction, braking or air resistance (34). Monark, a friction-braked ergometer, is the most frequently used stationary ergometer. In this project, a Monark 839E is used. The Monark 839E consists of a stable, heavy duty steel frame and a large, well balanced heavy flywheel. This ergometer is a belt braking device, as the pedals and chain drive spin the flywheel, as a tension device tightens the belt to regulate the braking force applied to the wheel. A pendulum indicates the amount of applied force directly on a scale located at the side of the flywheel. A motor in the ergometer adjusts the tension of the belt, which regulates the applied braking force. This enables the force to be automatically varied in response to changes in pedal speed to maintain a constant power workload. A main unit near the handlebar is able to display cadence, applied force in Newton, power in Watt, heart rate, distance, energy expended and time. The Monark 839E can apply braking forces that equal power outputs up to 1400 W at a maximum cadence of 200 RPM.

The described power meters all measure the power output one way or the other. However, other manufacturers uses an entirely different procedure.

iBike Is a bike computer capable of estimating the cyclist´s power output using equation (5). According to Newton´s third law when one body exerts a force on a second body, the second body simultaneously exerts a force equal in magnitude and opposite in direction on the first body (40). The forces in opposite direction from wind, grading, acceleration and friction will be equal to the applied pedal forces. The power output of the cyclist will be equal to forces in opposite direction multiplied by velocity. By measuring or estimating the forces in opposite direction and velocity, the power output can be computed. iBike uses a digital gradient sensor and measures the air density by registration of the static pressure and temperature, while the air humidity is ignored. The air density is used to compute the aerodynamically factors. The wind speed is calculated by measuring static and dynamic atmospheric pressure, and the air density. iBike measures the cycling speed, like most other bike computers, by having a sensor registering each time a magnet, fastened to the wheel, completes one revolution. Accelerometers measures the acceleration of the cyclist and bike. Finally the user enters the remaining necessary information such as weight of the rider and bike, wheel size, surface of the road, height of the rider and bike and position on the bike. The coefficient of rolling resistance and coefficient of aerodynamic drag is then computed. This procedure of estimating power output creates a number of sources of error such as the cyclist can change position, the rolling resistance can change during a ride and the air pressure of the tires can change. iBike is switched between bikes the same way any other bike computer is switched and adds approximately 300 g to the bike.

Measurement of pedal forces

The first reported use of measurement of force applied to bike pedals goes back to 1896, when Guye and Sharp used pressure sensors (7). It wasn't until 1968 before force measurement at the pedals where investigated carefully, when Hoes et al. used a sensor with a strain gauge localized at the center of the crank arm and a potentiometer at the point of attachment of the crank. This method was restricted to measuring forces in the Fz plane, which was considered adequate by the author. This was later questioned in 1981 when a dynamometer was developed that was capable of measuring the force components normal (Fz), anterior-posterior (Fx) and medio-lateral (Fy), and the moments My, Mx and Mz (7). The device was mounted under the pedal and consisted of 32 strain gauges and 2 potentiometers for measurement of the orientation of the crank and pedal. The dynamometer can be observed in figure 1.

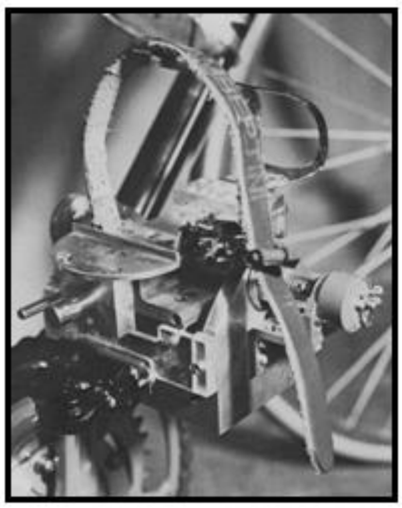


Figure 1 illustrates the dynamometer of Hull & Davis (7)

In line with development of new technology, the measurement of pedal forces has become more simple and precise. The majority of the systems have been used scientifically, but systems have also been developed for road cycling (2) and mountain bikes (37). The most common approach has been to measure pedal forces by using strain gauges. Other systems have used piezoelectric and piezoresistive sensors, and one study mounted an ergometer bike to a force plate and computed the pedal forces by using inverse dynamics (7). Lately, commercial systems such as Garmin Vector have also been developed. For now, all commercial systems are restricted to measuring power output and cannot display pedal forces (5).

The direction of the applied force to the pedals is dependent on the position of the foot in relation to the surface of the pedal. To enable analysis of the force direction on the pedal surface, the total pedal force is separated into three components; normal (Fz), anterior-posterior (Fx) and medio-lateral (Fy), see figure 2.

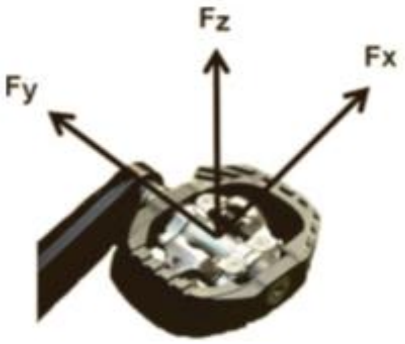


Figure 2 illustrates the three force components acting on a pedal (5).

Fy does not contribute to crank torque, which explains why most studies focused only on the other two force components. However, research has shown that increases in lateral force application on the pedal surface could be associated with overload on the knee joint soft tissues (38).

The total force applied to the pedal in the sagittal plane can be computed using the remaining two force components; Fz and Fx. A percentage of the total force applied to the pedal will be perpendicular to the crank and drive the crank. This percentage is called effective force and is responsible for propulsion of the bike. If you know the effective and total force, it is possible to compute the Index of Effectiveness (IE), which is the ratio between the impulse of the effective force and the total pedal force during one crank revolution (31):

$$IE = \frac{\int_0^{360} EF\,dt}{\int_0^{360} RF\,dt} \tag{6}$$

EF is the effective force and RF is the total force, also called the resultant force. By computing IE, it is possible to measure the technique of a bike rider, as it is an assessment of percentage of pedal forces that produce propelling power on the bicycle. As would be expected, more skilled riders are more effective than less skilled riders (8, 24, 25). The described force components and their direction can be observed in figure 3.

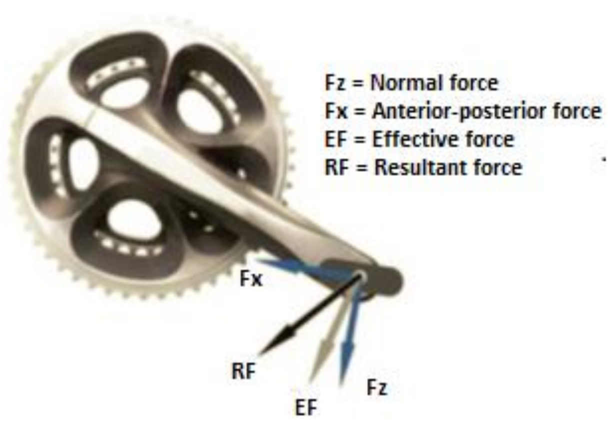


Figure 3 illustrates the pedal force components in the sagittal plane; normal (Fz) and anterior-posterior (Fx), and the effective force (EF), which is the percentage of the total force (RF), that is perpendicular to the crank (5).

To compute the effective force, the pedal angle in relation to the crank must be measured as the pedals coordinate system does not follow the cranks coordinate system. If pedal inclination is changed, so is the orientation of the normal force, see figure 4. Therefore, the inclination of the pedal has to be known in order to compute Fz and Fx from the pedal to the crank.

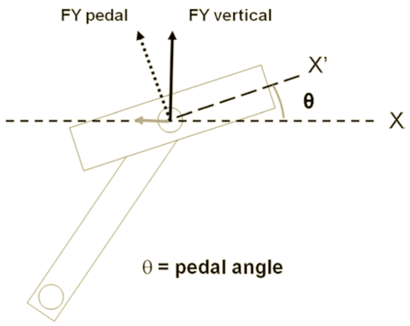


Figure 4 illustrates the importance of the inclination of the pedal in relation to the force components (5)

The inclination of the pedal is typically measured either by filming cyclists pedaling using cameras or by using angular sensors. The first method sometimes involves a long time spend on placing markers and synchronization with pedal force data. This method is further restricted to the laboratory. The second method employs angular sensor such as a potentiometer, goniometer or accelerometer fastened to the spindle of the pedal. The sensor tracks the rotation of the spindle of the pedal in relation to the motion of the crank. A change in voltage can then be converted to a change in angle using calibration. This method enables the signal to be directly synchronized with force data (5).

A number of sources of errors exist in the measurement of pedal forces. During calibration it is important to know the precise loads and angles. Furthermore, cross-talk can occur between the force components. This is caused by the Poisson effect, which describes how a material compressed in one direction will expand in another. Consequently, when a load is applied in the Fz axis on a pedal, it will result in an expansion in the Fx axis. The expansion will be minimal but still measurable by the sensors. A third source of error is drift in the measurement of force. Most sources of errors can be neglected by compensating mathematically (5).

The pedal cycle is often classified into two phases; downstroke and upstroke, or four parts, see figure 5. The ideal force direction is based on the assumption that all of the force applied to the pedal is to be converted into effective force. To create a maximum amount of propulsion from normal force, the rider should push down the pedal in the downstroke phase from the top dead sport to the bottom dead spot, and pull up the pedal from the bottom dead spot to the top dead spot. To create a maximum amount of propulsion from anterior-posterior force, the rider should push the pedal forward in the first and fourth part of the pedal cycle, and backward in the second and third part (7). However, these ideal force profiles are not observed in cyclists, in particular during the upstroke phase (26, 30). A typical force profile is seen in figure 6. It can be observed that the force is approximately perpendicular to the surface of the pedal.

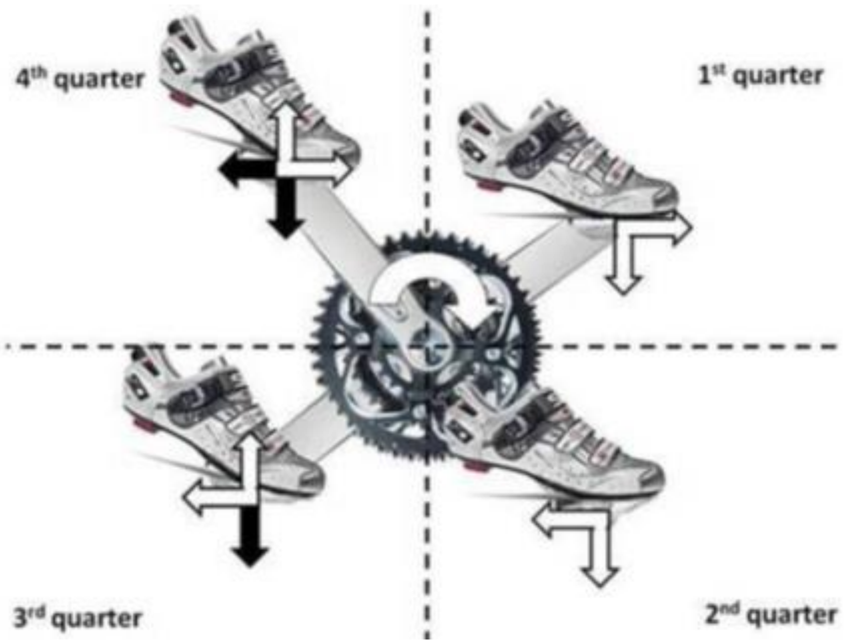


Figure 5 illustrates an ideal force application to the pedal. The pedal cycle is divided into four parts. White arrows indicates the ideal force application in relation to optimizing the effectiveness of force, while the black arrows are examples of a typical force application of a rider (7).

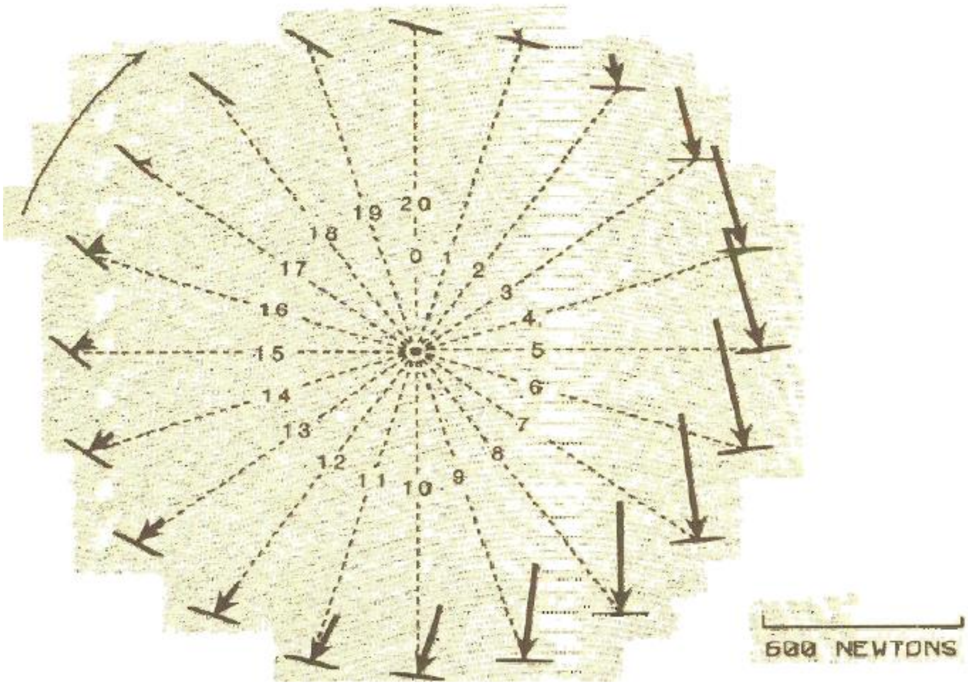


Figure 6 illustrates a typical force profile.

The majority of the effective force is produced during the downstroke phase and peaks at an angle of approximately 90°(12), which can be seen in figure 7, where a cyclist produces 350 W. A study has shown national and international sprinters to be able to produce up to 2400 N and pedal forces of up to 900 N (11). Propelling effective force is rarely produced in the upstroke phase. Research has on the contrary found that several cyclists produce negative effective force during the upstroke phase (18, 36, 39). When this is the case, the effective component of pedal force is in the opposite direction in relation to crank motion and the force is opposing the opposite leg (12). This can be observed in figure 8, in which the effective force is negative in the third and fourth part of the crank revolution.

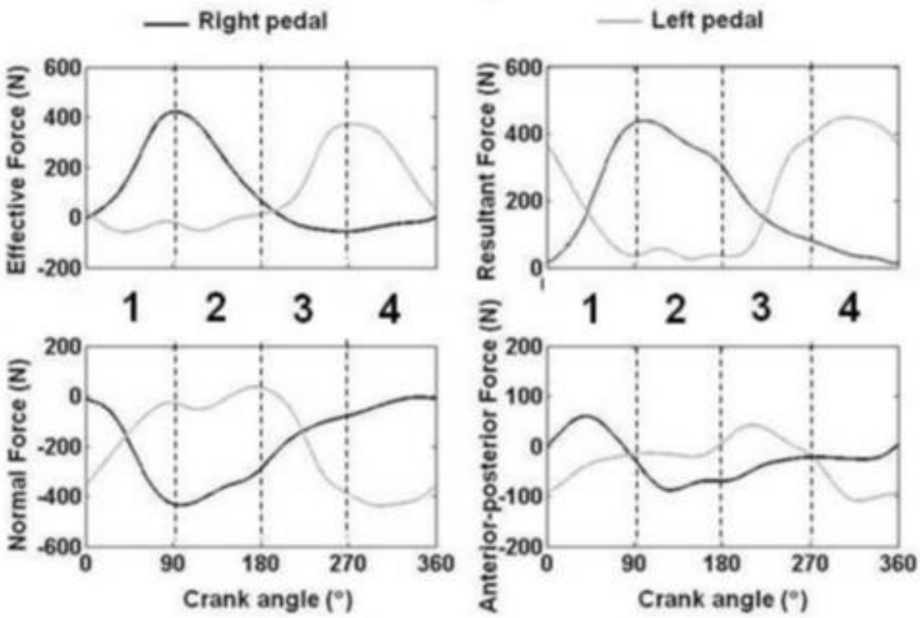


Figure 7 illustrates effective, total, normal and anterior-posterior force for a typical cyclist in relation to crank angle. Positive values for effective force is an indication of propelling force. Positive values for normal force is an indication of pulling the pedal. Positive values for anterior-posterior is an indication of pushing the pedal forward (7).

As previously mentioned only Fx and especially Fz contributes to propulsion of the bike. Fy however, can have values of up to 50 N at a power output of 250 W, see figure 8.

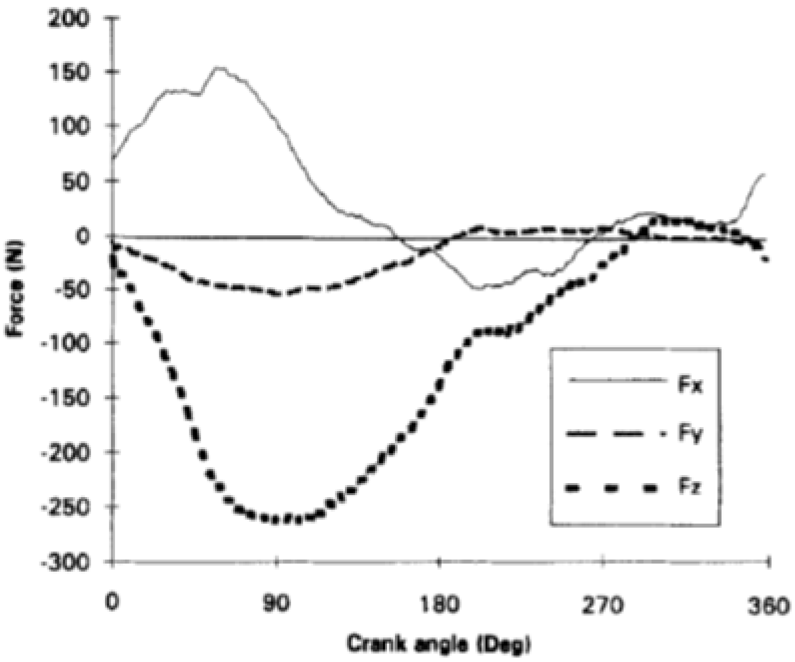


Figure 8 illustrates the magnitude of the force components Fz, Fy and Fx at a power output of 250 W (7).

Danfoss PolyPower

Dielectric electroactive polymer

A specific type of polymers called electroactive polymers (EAP) are able to change their shape or size when stimulated electrically. EAP´s are especially popular in research of artificial muscles on robots because of the low price and energy demands. Two types of EAP´s exists; ionic and electric (9). The electric EAP´s can further be divided into two groups; Dielectric electroactive polymers (DEAP) and Liquid Crystal Elastomers, which are used in LCD televisions. DEAP is considered a technology with a huge potential because of its flexibility and elastic properties. DEAP is basically an elastomer film coated with electrodes on both sides. The electrodes are connected to a circuit and when a voltage or a force is applied, the material is compressed, resulting in an electrostatic pressure, see figure 9. DEAP is versatile in the sense that the technology can be used as actuator, generator and sensor (15).

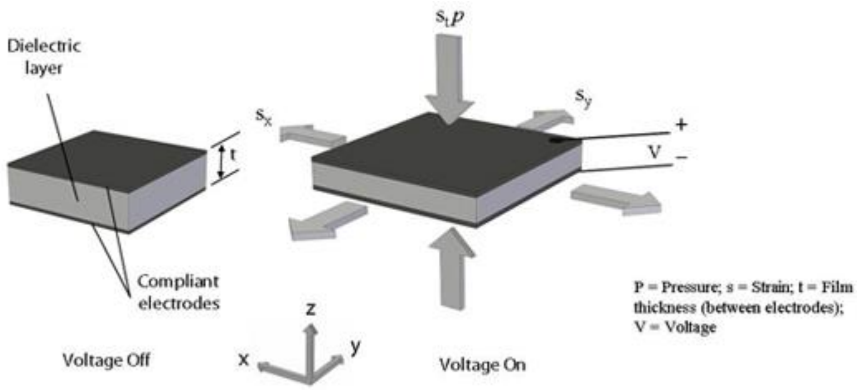


Figure 9 illustrates the principle behind DEAP (15).

When DEAP is used as an actuator, the elastomer films are charged with opposite polarity, resulting in the attraction of the electrodes. Consequently, the films are compressed and a pressure (ρ) is created. The volume is kept constant even though the thickness of the films are reduced because the area is increased. The elastomer film draws together to their original shape, when the charging is stopped. The pressure that is created on the silicone layer as a consequence of the compression can be described using the Maxwell pressure (3):

$$\rho = \epsilon_r \epsilon_0 E^2 = \epsilon_r \epsilon_0 (\frac{V}{t})^2 \quad (7)$$

ρ is the electrostatic pressure on the electrodes, ϵ_r is the relative permittivity of the polymer, ϵ_0 is the vacuum permittivity, E is the electric field strength, V is the voltage and t is the DEAP film thickness.

When DEAP is used as a generator mechanical energy is converted into electric energy by stretching the elastomer films and then charging and discharging the films resulting in an increase in voltage.

In this project, it is the ability of DEAP´s to be used as a sensor that is interesting. The dielectric silicone material acts as a capacitor in the way that a mechanical deformation caused by an applied force results in changes in capacitance, which can be correlated with the applied deformation. The correlation is observable in the following equation, which describes how the capacitance is measured when the material is not deformed.

$$C_0 = \epsilon_r \epsilon_0 (\frac{A}{t}) \quad (8)$$

C_0 is the capacitance and A is the area.

Because ϵ_r and ϵ_0 are constants, the only way to change the capacitance is to change the area and/or thickness of the material, which are dependent on the magnitude of the applied force. The capacitance is dependent on the strain of the material and because strain is related to force and displacement, DEAP´s can be used as position, pressure and force sensors. So far, research on DEAP has been focusing on its ability as an actuator. A study (29) however, found that a strain sensor based on DEAP technology was capable of measuring the navicular drop with a precision equivalent to a motion capture system. DEAP´s have also been shown to be useful as a pressure sensor (27).

DEAP´s can be described as electromechanical transducers, as they are capable of converting mechanical energy to electric energy or vice versa.

Danfoss PolyPower sensor

Recently Danfoss PolyPower A/S developed a special optimized DEAP called PolyPower. PolyPower consists of two layers of dielectric silicone material with a thin layer of elastomer films with silver electrodes along the sides. In between the two layers and at the outer sides of the electrodes are also layers of silicone. The silicone acts as a semiconductor, keeps the sensor together and protects the electrodes against physical contact (13). The electrodes are negatively charged at the outer side and positive at the inner side in order to prevent physical contact, which can act as a conductor.

Figure 10 illustrates the structure of the sensor material. The capacitance is measured as an average of the two electrical fields (13).

The uniqueness of PolyPower compared to other DEAP´s is the micro-wrinkled surface with a sine wave shape, which makes one plane stiffer than the other. Because of this feature, the material is easily stretched along the waves but hardly stretchable across the waves, see figure 11. The materials mechanical properties can therefore be said to be anisotropic. Consequently, equation (8) is incomplete as the anisotropy must be taken into account in the computation of capacitance (13). The capacitance for PolyPower is instead computed using equation:

$$C = C_0(1+S)^{1.8} \tag{9}$$

C is the capacitance in the deformed sensor material, C_0 is the capacitance in the non-deformed sensor material , S is the strain and 1.8 is the degree of anisotropy in the material.

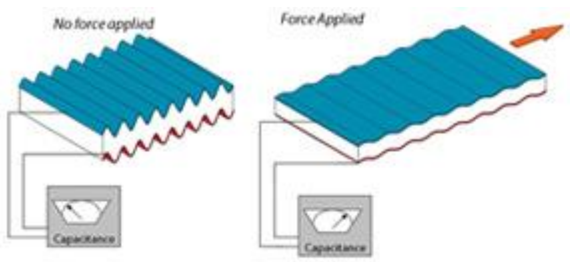


Figure 11 illustrates the unique waveform of PolyPower and how the capacitance is increased when a force is applied (13).

Lifetime

If PolyPower is to be used as a force sensor, it is important the lifetime is acceptable. The PolyPower film has been tested with a strain of up to 50 % and can survive at least four million cycles (13).

Environmental considerations

If the force sensor is to be used on a bike, the sensor needs to be able to work in different environments. Studies have shown the modulus of elasticity to be constant in the region of -50 °C to 75 °C. At higher temperatures the results begin to vary. Danfoss PolyPower recommends that the sensor is used in the range of -20 °C to 80 °C (16). Water intake can affect DEAP and water intake in silicone is relatively fast compared to other polymers. As a consequence, the force sensor should not be exposed to water at all. In addition, studies have shown that PolyPower is affected by moisture (13). If PolyPower is used as a force sensor on a bike, the sensor should at all times be protected from the surroundings in order to avoid water and moisture.

PolyPower force sensor

The PolyPower force sensor consist of a sensor area with the film and electrodes. The sensor area is a square with a height and width of 2.1 cm. At the end of the sensor area a cable transports the signal from the sensor material to a control box using a jack plug. Surrounding the sensor area is a silicone layer, which protects the area, but at the same time is an integrated part of the sensor area, in the sense that deformation in the silicone layer results in a stretch of the sensor area. This can be explained by the Poisson effect, which states that compression in one direction creates expansion in another. The silicone layer has a thickness of 0.8 cm and the sensor area is attached to the center. The force sensor can be observed in figure X.

Figure 12 illustrates the PolyPower force sensor

Torque

Whenever a force is applied to an object, e.g. a pencil on a desk, some kind of motion will occur. If the applied force is parallel to the desk and through the center of the pencil, the pencil will be translated in the direction of the force. If the force is directed through a point other than the center of the pencil, the pencil will also undergo rotation. The rotary effect is known as torque or moment of force and can be thought of as rotary force. In planar cases, the torque (τ) is the product of force (F) and the perpendicular distance (d) from the force´s line of action to the axis of rotation, known as the lever arm (21):

$$\tau = F \cdot d \quad (10)$$

When the torque is increased, the tendency to rotation in the object is increases as well. The lever arm is always the shortest distance between the force´s line of action and the axis of rotation. The torque is normally stated as positive when the force acts counterclockwise and negative when the force acts clockwise (40). The SI unit for torque is Newton meter (Nm).

Accelerometers

Accelerometers are electromechanical devices that measures acceleration forces and converts it into an electric signal. These forces can either be static or dynamic. Static acceleration, or gravitational acceleration, is due to the gravitational force, which is constant. The dynamic acceleration is the acceleration due to any other force than the gravitational force applied on a rigid body and are caused by moving or vibrating the accelerometer (17).

When measuring the amount of static acceleration due to gravity, it is possible to calculate the angle the device is at with respect to the earth. When measuring the dynamic acceleration, it is possible to analyze the way the device is moving. Accelerometers are helpful in understanding the surroundings/environment of an object. Accelerometers can determine if the object is moving and in which direction. For example, recently Apple and IBM have started using accelerometers in their laptops. If you accidently drop the laptop, accelerometers detects the sudden change in acceleration and switches the hard drive off to prevent damage. Detecting car crashes and deploying air bags at just the right time function in a similar way (17).

Accelerometers can differ in number of axes, maximum swing, sensitivity, bandwidth and if the output is analog or digital. Moreover, accelerometers are typically based on one of the following three techniques:

- Piezoelectric effect – These accelerometers contain microscopic crystal structures. When compressed due to a force caused by acceleration, or subject to a shearing force, a proportional electrical signal is generated. Piezoelectric accelerometers are especially suited for high frequency vibrations.
- Capacitance changes – These accelerometers sense the change in capacitance between two microstructures next to each other. When an accelerative force moves one of the structures, the capacitance changes.
- Thermal accelerometer – A heater heats up a small bubble of air inside the thermal accelerometers. When a force is applied on to the accelerometer, the position of the heated air bubble changes. The movement of the hot air bubble is then measured by temperature sensors and converted to an electrical signal (17).

Test of mechanical properties

The mechanical properties of materials can be investigated and measured by use of materials testing machines. These machines contains force transducers, and are typically found either in mechanical or hydraulic editions. Materials can either be tested during compression or pulling. The machine is set to a certain deformation speed and measures the force necessary to maintain the deformation speed. The deformation of the material is also measured. The relation between force and deformation in absolute units is then observable as a working curve as seen in figure 13. The stiffness of the material can be described by the inclination of the curve. Not all materials display a linear force-deformation relation and the stiffness often vary depending on the magnitude of elongation or compression of the material. Several materials, e.g. elastomers, display a curved first part of the curve. This is because the chain molecules are curled together when the material is at rest, and when compressed or pulled, the molecules are straightened (20).

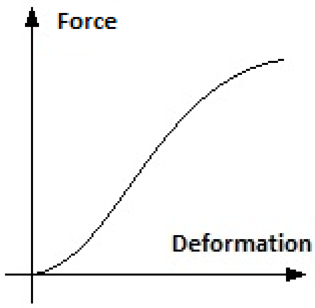


Figure 13 illustrates a working curve

The area under the curve represents elastic potential energy stored in the material. A great portion of this energy can be released as mechanical energy if the yield point is not exceeded. When a material is loaded and unloaded, the two curves will follow a different path. The area between the curves is the amount of energy loss caused by inner friction, which causes the elastic energy to dissipate into heat. This phenomenon is called hysteresis and can be seen in figure 14. Materials exhibiting a high amount of hysteresis are often used as dampers. A completely elastic material would show no signs of hysteresis. The magnitude of friction is often dependent on the deformation speed. When the loading or unloading is fast, the distance between the curves will be greater, while the curves are closer together at a slow deformation speed. This is called viscoelasticity and is observable in nearly every material to some degree (20).

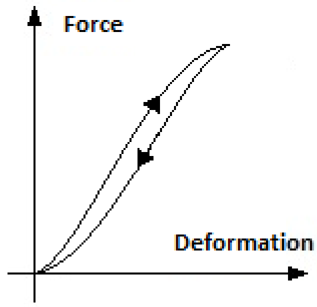


Figure 14 illustrates a working curve with a hysteresis loop

Method

Development of power meter device

The main purpose of this project has been to mount a PolyPower force sensor from Danfoss PolyPower A/S in the connection between foot and bike pedal, and function as a power meter. Most power meters in this connection, measures the force applied to the pedal. When the bike rider wants to ride another bike and use the same power meter, the pedals have to be switched. To avoid this, it was decided to place the force sensor at the cycling shoe. This way, the power meter becomes wearable as it is attached to the rider and not the bike. Because of the force sensor´s size, it was deemed impossible to place the sensor in the sole of the cycling shoe. Instead, it was decided to mount the sensor between the cycling shoe and cleat, which is used to attach the shoe to the pedal. The cleat that was used is a Shimano SM-SH11 cleat, which fits all Shimano pedals.

The shape of the cleat results in the transfer of force from shoe to sensor to pedal is less than optimal. Therefore, the sensor is placed in between two identical plates of aluminium (Aluminium alloy 6060) shaped as an isosceles trapezoid. The plates have a length of 6.5 cm, a maximal width of 8 cm and a minimal width of 4 cm. Aluminium is chosen because it is a light metal but at the same time strong and durable, which fits the purpose of this project as it is loaded several times. When a force is applied to the plates, they deform the sensor, which measures a change in capacitance. Three holes matching those of the cleat and shoe were drilled into the plates to enable the device to act as a connecting link between the cleat and shoe. At first, the holes were drilled with a diameter of 0.5 cm. Because of the bended cycling shoe, the machine bolts are at an oblique angle so to avoid friction, the holes were increased to a diameter of 1 cm. The machine bolts that were used, had a length of 4 cm. The upper part of the machine bolts were without screw thread to avoid friction between the bolts and plates.

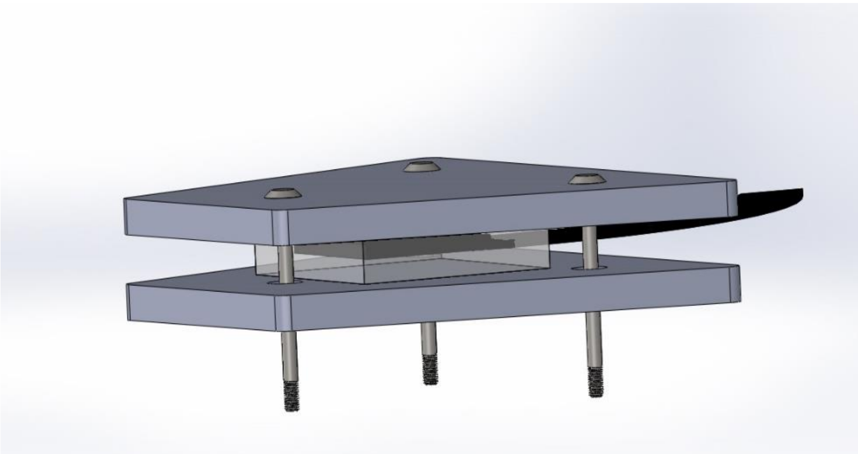


Figure 15 illustrates a Computer-aided design (CAD) drawing of the power meter device

To further reduce this friction, the bolts were lubricated with Super Lube® Multi-Purpose Grease (Super Lube, New York, USA).

As some riders pull the pedal upwards during the pedal cycle, rubber washers were inserted between the head of the bolt and plate to be able to measure the pulling force. The bolts were tightened, which created a pretension in the force sensor. When the device is pulled, the top plate is pulled upwards because of the rubber washers and the sensor will measure a drop in force.

A technical drawing of the plate was made and handed out to a craftsman at a machine shop, who manufactured two plates.

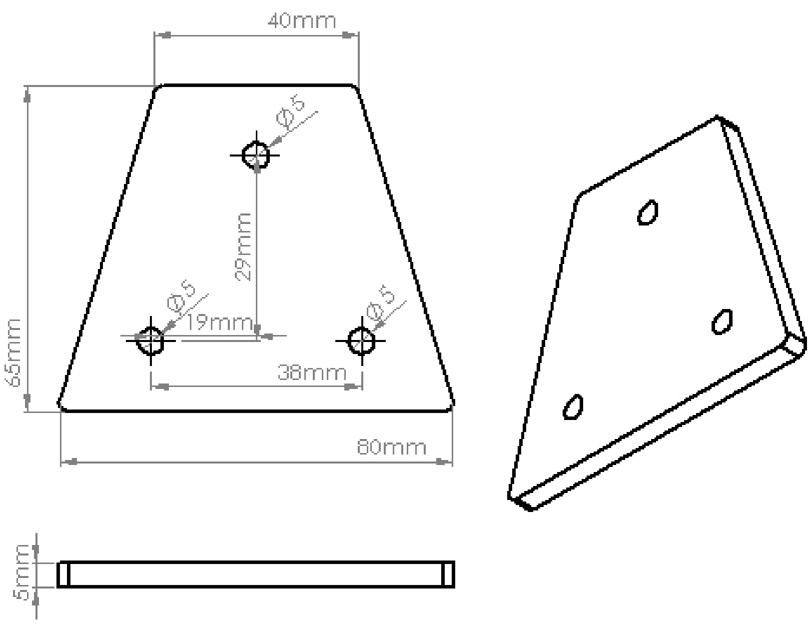


Figure 16 illustrates the technical drawing of the aluminium plates

The total weight of the power meter device is 181 g with a height of approximately 1.8 cm.

Figure 17 illustrates the manufactured power meter device

Due to the construction of the power meter device, the sensor is able to record the normal force that is applied. It is only the force vector acting perpendicular to the crank that produces propelling power on the bicycle. This force is called effective force and if crank angle and pedal angle is known, it can be computed using basic trigonometry. The angle of the crank and pedal was obtained using two accelerometers (Shimmer3, Shimmer, Dublin, Ireland). Specific software (LabVIEW, National Instruments, Austin, USA) was used for recording and sampling data at 512 Hz. One accelerometer was mounted at the center of rotation of the crank and the other at the center of rotation of the pedal. Angular acceleration was converted to angle using trigonometry. The measurement of crank and pedal angle by the accelerometers was validated by comparing a pedaling trial with a high-speed camera (Basler AG, Ahrensburg, Germany) recording at 350 fps. The accelerometers and the force sensor transmitted data to a computer using Bluetooth.


Figure 18 illlustrates the crank and power meter device at different angles during pedaling

The pedal torque (PT) was calculated as follows:

$$PT = F_{eff} \cdot L \qquad (11)$$

where F_{eff} is effective force and L is the distance in meters from crank spindle to the pedal spindle (0.170 m).

The angular velocity of the rotating crank (ω) expressed in radians per second (rad·s^{-1}) was obtained from the pedaling cadence (C), expressed in revolutions per minute (RPM), recorded by the ergometer:

$$\omega = \frac{C \cdot 2 \cdot \pi}{60} \qquad (12)$$

The power output was (P) expressed in Watts (W) as the mean value for every two seconds was calculated as follows:

$$P = PT * \omega \qquad (13)$$

Calibration of power meter device

The power meter device was calibrated by applying known vertical loads of 0 N, 20 N, 40 N, 60 N, 80 N and 100 N using a Zwick Z100/TL3S materials testing machine (Zwick GmbH & Co. KG, Germany). When loaded, the corresponding capacitance reading from the force sensor in the power meter device was recorded.

Validation of power meter device

To test the validity and reliability of the power meter device, it was compared to a Monark 839 stationary ergometer (Monark Exercise AB, Vansbro, Sweden) with clipless pedals (Shimano 105 PD-R540 SPD-SL, Shimano Inc, Japan). The Monark 839 is a mechanically weighted and braked ergometer, where the work performed on the ergometer is the product of the weight lifted times the numbers of revolutions. The Monark 839 is not able to store data but can be set to a constant workload or an incremental protocol, where the workload is constantly increasing with time. The power meter device was mounted in between a cycling shoe and cleat, and attached to the right pedal, and force was recorded and sampled at 50 Hz using sensor software (Wireless Sensor Controller, Danfoss PolyPower A/S, Nordborg, Denmark). The power meter device was pretensioned with a force of 38 N. This test setup only measures the power output of the right leg, which is doubled to estimate the total power output. This method is similar to the commercially available system Stages and could produce erroneous results if the cyclist is injured or asymmetric in pedaling style.

A recreational male cyclist (age: 25 years old, height: 1.79 m, body mass: 76 kg, weekly cycling training: 4 hours) volunteered as subject for this study. Prior to testing and after having been explained the nature and the purpose of the study, the subject gave written informed consent. The subject performed a 15 min. self-chosen warm up session, which also acted as habituation to the test setup. Prior to the warm up, the seat height was adjusted to fit the subject.

After the warm up, the Monark ergometer was calibrated according to the instructions of the manufacturer.

Following a ten minute break, the subject performed the experimental protocol in a laboratory at room temperature. The protocol consisted of:

- Sub-maximal 2-min continuous tests with constant workloads of 50 W, 100 W, 150 W and 200 W at 60 RPM. 2 min break between workloads. This protocol was repeated three times.

- Sub-maximal 2-min continuous tests with constant workloads of 50 W, 100 W, 150 W and 200 W at 90 RPM. 2 min break between workloads. This protocol was repeated three times.
- An incremental test of increasing workload of 2 $W \cdot s^{-1}$ from 50-200 W at 60 RPM.

Determining mechanical properties of rubber washers and force sensor

The pretension mechanism, which allows the device to measure pulling forces, is constructed using rubber washers. When the device is pulled, the rubber washers are compressed, which requires a certain amount of force. The amount of force that is used to compress the rubber washers can be computed by performing a compression test of respectively the rubber washers and force sensor in order to find the correlation between force and deformation. Consequently, because the sensor measures the change in capacitance, which can be converted to force, the deformation of the sensor is known at all times. Because of the way the device is constructed, the change in deformation of the rubber washers is the opposite of the sensor´s. When the deformation of the rubber washers are known, the force needed to compress the rubber washers is also known.

The compression tests of three rubber washers and the force sensor were performed at room temperature. Measurements of force and deformation were collected using a Zwick Z100/TL3S materials testing machine (Zwick GmbH & Co. KG, Germany), see figure 19. The rubber washers were one at a time subjected to 10 measurement cycles from 0-100 N at the fastest deformation speed of 200 mm/min. Force and deformation data were acquired at 50 Hz. Immediate observations showed small signs of plastic deformation. Consequently, trials with 25 measurements cycles for each rubber washer were performed. This trial did not show further signs of plastic deformation.

Subsequently, the force sensor was subjected to 10 measurement cycles from 0-300 N at the fastest deformation speed of 200 mm/min with measurements every 20 ms.

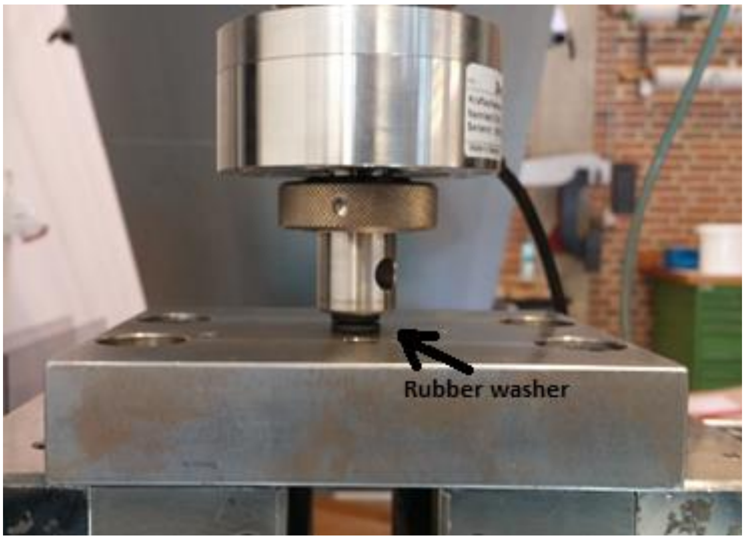


Figure 19 illustrates the compression test of the rubber washers

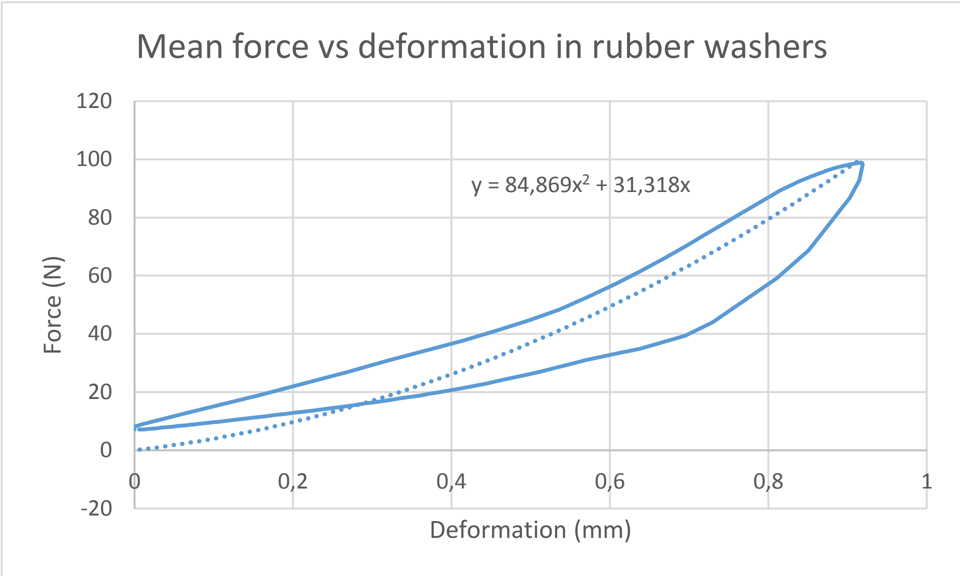
Results and data processing

Compression tests

A mean hysteresis loop was created from the measurement cycles of the three rubber washers.

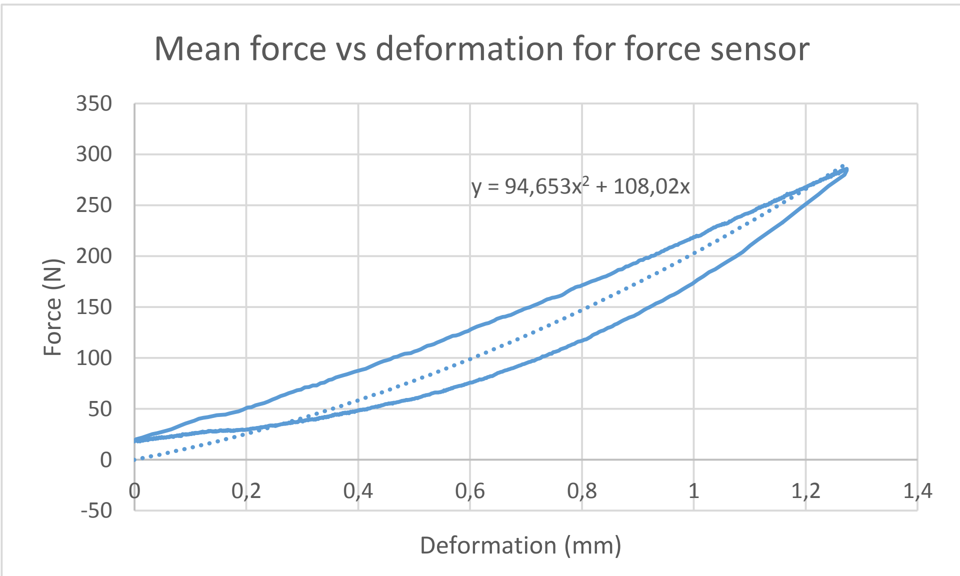
Using Excel (Excel 2013, Microsoft, Seattle, USA) a 2nd order polynomial trend line was calculated:

$$y = 84{,}869x^2 + 31{,}318x$$



A mean hysteresis loop was created from the measurement cycles of the force sensor. Using Excel, a 2nd order polynomial trend line was calculated:

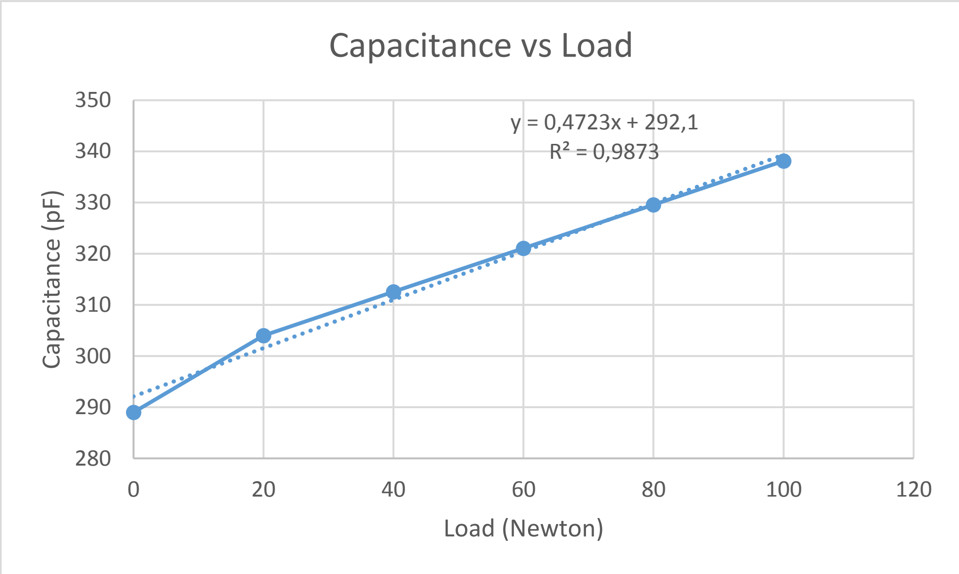
$$y = 94{,}653x^2 + 108{,}02x$$



Calibration of device

The relationship between load and capacitance for the power meter device was investigated using the measurements from the calibration of the power meter device. Using Excel, a linear trend line was calculated:

$$y = 0{,}4723x + 292{,}1$$



MatLab script

The following MatLab script was used to convert the accelerometer measurements into the angle of the pedal in relation to the crank:

```
record = '150w-60rpm'

switch record
    case '150w-60rpm'
        offset = 1;
end

file = strcat(record,'_krank.mat');

load(file)

time = [0:length(time)-1]./512;

Fs = 512;

[b,a] = cheby2(4,60,10/(Fs/2));
acc_x_filt = filtfilt(b,a,acc_x);
acc_y_filt = filtfilt(b,a,acc_y);
acc_z_filt = filtfilt(b,a,acc_z);
```

```
gyro_x_filt = filtfilt(b,a,gyro_x);
gyro_y_filt = filtfilt(b,a,gyro_y);
gyro_z_filt = filtfilt(b,a,gyro_z);

omega = gyro_z_filt;

figure
S1 = subplot(3,2,1);
hold off
plot(time,acc_x_filt,'r')
hold on
plot(time,acc_y_filt,'g')
plot(time,acc_z_filt,'b')
plot(time,sqrt(acc_x_filt.^2 + acc_y_filt.^2 + acc_z_filt.^2),'k')
title(strcat(record,'-krank'))

S2 = subplot(3,2,3);
hold off
plot(time,gyro_x_filt,'r')
hold on
plot(time,gyro_y_filt,'g')
plot(time,gyro_z_filt,'b')

S3 = subplot(3,2,5);
hold off
X = acc_x_filt - mean(acc_x_filt(4000:14000));
Y = acc_y_filt - mean(acc_y_filt(4000:14000));

plot(X,Y,'k')
line([-12 12],[0 0 ])
line([0 0],[-12 12])

axis equal

figure(2)
plot(180/pi*atan2(Y,X),sqrt(acc_x_filt.^2 + acc_y_filt.^2 + acc_z_filt.^2),'k.')

%%

file = strcat(record,'_sko.mat');

load(file)

time = [0:length(time)-1]./512;
time = time(offset:end);

Fs = 512;

[b,a] = cheby2(4,60,10/(Fs/2));
acc_x_filt = filtfilt(b,a,acc_x(offset:end));
acc_y_filt = filtfilt(b,a,acc_y(offset:end));
acc_z_filt = filtfilt(b,a,acc_z(offset:end));

gyro_x_filt = filtfilt(b,a,gyro_x(offset:end));
gyro_y_filt = filtfilt(b,a,gyro_y(offset:end));
```

```
gyro_z_filt = filtfilt(b,a,gyro_z(offset:end));

figure(1)
S4 = subplot(3,2,2);
hold off
plot(time,acc_x_filt,'r')
hold on
plot(time,acc_y_filt,'g')
plot(time,acc_z_filt,'b')
plot(time,sqrt(acc_x_filt.^2 + acc_y_filt.^2 + acc_z_filt.^2),'k')
title(strcat(record,'-sko'))

S5 = subplot(3,2,4);
hold off
plot(time,gyro_x_filt,'r')
hold on
plot(time,gyro_y_filt,'g')
plot(time,gyro_z_filt,'b')

Start_angle = atan2(-acc_z_filt(1),-acc_x_filt(1))*180/pi

S6 = subplot(3,2,6);

X2 = acc_x_filt - mean(acc_x_filt(4000:14000));
Z2 = acc_z_filt - mean(acc_z_filt(4000:14000));

hold off
plot(X2,Z2,'k')
axis equal

linkaxes([S1 S2 S4 S5],'x')

Pedal_angle = detrend(cumsum(gyro_y_filt)./512);
Pedal_angle = Start_angle + Pedal_angle - mean(Pedal_angle(1:1000));

figure(3)
plot(time,Pedal_angle)

figure(4)
Crank_angle = 90 + (-180/pi*atan2(Y,X)) * -1;

L = min([length(Pedal_angle) length(Crank_angle)]);
plot(Crank_angle(1:L),Pedal_angle(1:L),'k.')
title(strcat(record,'-crank-versus-pedal'))

figure(5)
hold off
plot(time(1:L),(omega(1:L)*2*pi/360).^2.*0.17.*sin(Crank_angle(1:L)*pi/180))
hold on
plot(time(1:L),2*pi/360.*gyro_y_filt(1:L))

Angle = Pedal_angle(1:L) - Crank_angle(1:L);
Angle_ds = downsample(angle,7);
```

The following MatLab script was used to convert the raw capacitance data from the force sensor to total force:

```
Cap_pF = Capacitance_nF * 1000;
Cap_pF_offset = Cap_pF - mean(Cap_pF(0:100));
Total_force = Cap_pF_offset / 0.4723;
```

The following script was used to convert total force into power output:

```
Effective_force = Total_force * cos(Angle_ds*pi/180);
Pedal_torque = Effective_force * 0.17;
Power_output = Pedal_torque * angular_velocity;
```

Other design ideas

As the manufactured power meter device shows some limitations, such as an inability to measure anterior-posterior forces, a couple of other design ideas, which potentially could solve this problem, are proposed in the following part.

The first design idea uses two PolyPower force sensors instead of one. The idea is to place the sensors in a construction such as the one seen in figure 20. The inside height of the construction would be slightly lower than the height of the sensors, which would create a pretension in the device. Because of the shape of the sides, which are slightly thinner than the top and bottom, the device should be able to be compressed or elongated, when a force is applied or if the device is pulled, acting much like a spring. In addition, the top plate should be able to ´tip´ forwards and backwards when both a normal and anterior-posterior force is applied. Assuming that the vertical force acts exactly between the force sensors and that the length of the moment arm of the horizontal component is known, it should be possible to measure the moment applied to the tipping plate and find the anterior-posterior force. Screw holes would be made at the top and bottom plate to attach the construction to the cleat and shoe.

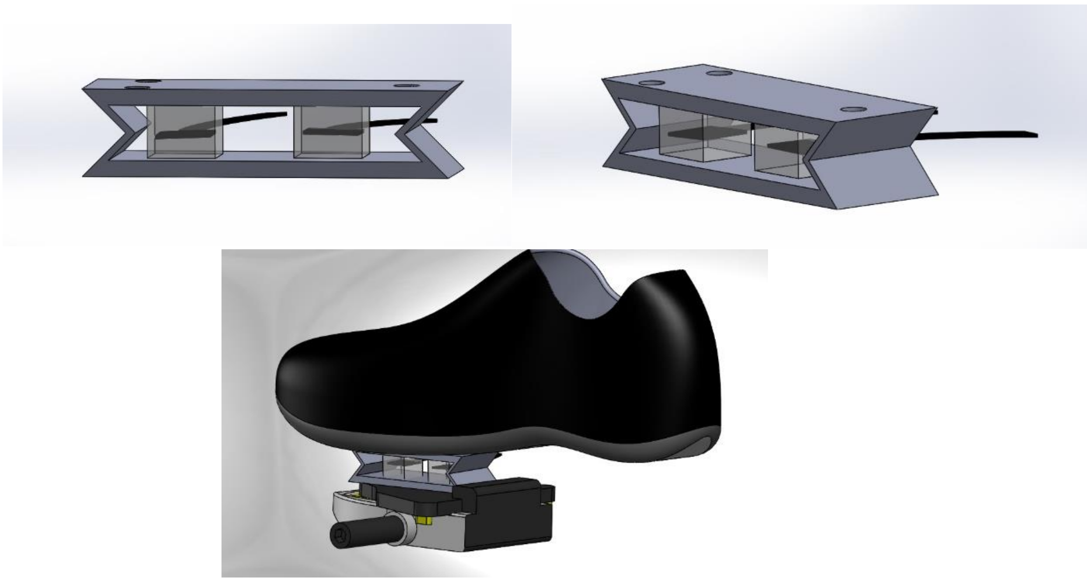


Figure 20 illustrates CAD drawings of a power meter device, which potentially could measure horizontal force

The possibility of manufacturing the construction was discussed with a craftsman from a machine shop. The craftsman was under the impression that the construction would be too stiff and not be able to provide the proper deformation. Thereby, the desired spring effect would not materialize. However, the Swedish company Sensible Solutions have voiced the possibility of using their 3D printer to manufature the constructrion in titanium, which should be able to provide the intended spring effect. Unfortunately, this was not possible before the end of this project.

Another design idea could be to replace the PolyPower force sensors with a plate containg strain gauges or similar load cells. This idea would use the same force measurement technique as many other power meters but the placement of the force measurement would still be unique. The idea would be to have a metal plate in between the cycling shoe and cleat without the cleat and shoe touching each other to insure that all the applied force is transferred through the plate. At first, the plate would be attached to the shoe before the cleat would be attached to the plate using screws. The plate would contain strategically placed strain gauges to make it possible to measure normal and anterior-posterior forces. This design would also decrease the height of the construction, which means the cycling shoe would be closer to the pedal.

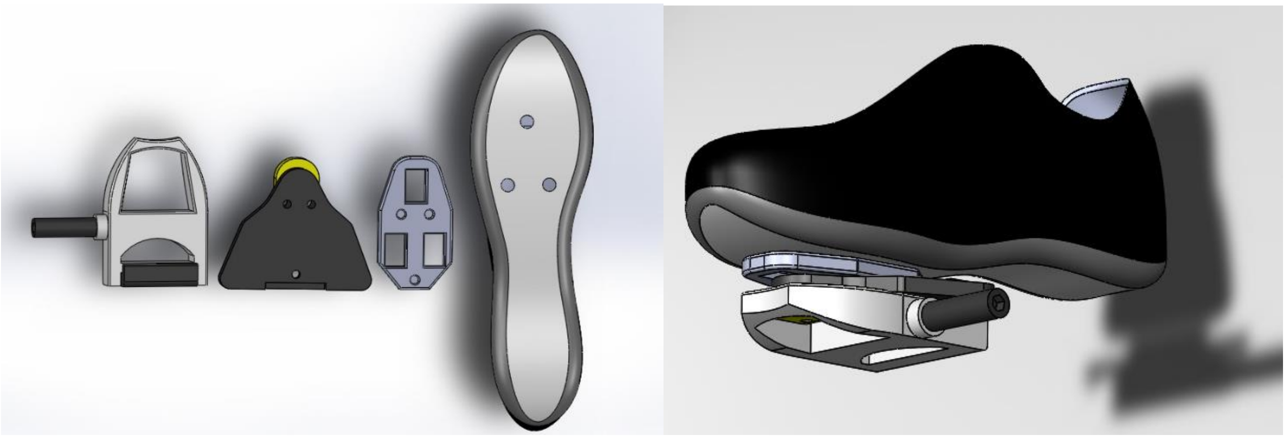


Figure 21 illustrates CAD drawings of a power meter device that uses strain gauges

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Appendix

Written consent

Informeret samtykke til deltagelse i et forskningsprojekt

Forskningsprojektets titel: **Development and evaluation of a novel power meter device in cycling: a proof of concept study**

Erklæring fra forsøgspersonen:

Jeg har fået skriftlig og mundtlig information og jeg ved nok om formål, metode, fordele og ulemper til at sige ja til at deltage.

Jeg ved, at det er frivilligt at deltage, og at jeg altid kan trække mit samtykke tilbage.

Jeg giver samtykke til at deltage i forskningsprojektet og har fået en kopi af dette samtykkeark samt en kopi af den skriftlige information om projektet til eget brug.

Forsøgspersonens navn: ____

Dato: ________________ Underskrift: ____

Ønsker du at blive informeret om forskningsprojektets resultat?:

Ja_____(sæt x)   Nej______ (sæt x)

Erklæring fra den forsøgsansvarlige:

Jeg erklærer, at forsøgspersonen har modtaget mundtlig og skriftlig information om forsøget.

Efter min overbevisning er der givet tilstrækkelig information til, at der kan træffes beslutning om deltagelse i forsøget

Den forsøgsansvarliges navn:____

Dato:___________________ Underskrift:____