DEVELOPMENT OF A NOVEL DEVICE FOR MEASUREMENT OF PEDAL FORCE IN CYCLING

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A device was developed to be mounted between a cycling shoe and cleat with the ability to measure force perpendicular to the pedal. The device consists of a PolyPower force sensor placed in between two aluminium plates connected by three bolts. Furthermore, a mechanism allowing pulling forces to be measured is explained. The device was comparable to a golden standard when pushed upon, but did not provide valid measurements of pulling forces. In order to function as a valid and reliable power meter or a device capable of measuring pedal forces, the sensor´s recovery rate should be improved along with the pulling mechanism of the device while angular sensors could be added for assessment of pedal kinematics.

KEY WORDS: cycling, pedal force, PolyPower sensor.

INTRODUCTION: The measurement of pedal forces is important because the forces applied to the pedals generate the propulsion of a bicycle and makes it possible to measure the left and right balance of the cyclist, which can be useful, especially during a rehabilitation phase. Furthermore, measurement of pedal forces enables assessment of a cyclist´s technique using the Index of effectiveness, which is the ratio of perpendicular force to the crank and total force applied to the pedal (Bini, Hume, Croft & Kilding, 2013). The application of pedal forces has also been used in biomechanical studies, to show a connection between muscle activity and force production (Bini, Hume, Croft & Kilding, 2013). If one would measure the power output of a rider, measuring the force at the pedals is advantageous compared to, for example the crank, as it would be faster and easier to switch the power meter between bikes.
During the last 50 years, different systems have been used to measure pedal forces on bicycles. The most common approach has been to use strain gauges as the force sensor but systems using sensors based on piezoelectricity, the Hall effect and piezoresistive effect have also been developed (Bini, Hume, Croft & Kilding, 2013).
Danfoss Polypower A/S has recently developed a Dielectric Electroactive Polymer called PolyPower, with the ability be used as force sensor. When deformed, the PolyPower changes its electrical properties and provides an output that is proportional to the amount of deformation. 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 not previously thought of. Therefore, the aim of this study was to develop and produce a prototype device, containing a PolyPower sensor, that could be mounted in the connection between a cycling shoe and pedal.

METHODS: Based on the aim of the study, it was decided to develop a device with the ability to be mounted between a cycling shoe and cleat.
A design, where the PolyPower sensor was placed in between two plates shaped as an isosceles trapezoid with screw holes placed to fit those of a Shimano SM-SH11 cleat (Shimano Inc., Sakai, Japan), was proposed. This enables the plates to be tightened to the cleat and shoe, and act as the connecting link.
Two aluminium plates (aluminium alloy 6060) with a length of 10 cm, height of 0.5 cm and a maximal and minimal width of respectively 10 and 4 cm were used. To connect the aluminium plates, three holes were constructed in both plates with screw thread in the bottom plate. This allows the screws to be pushed through the top plate and tightened to the

other. Force applied to the top plate will push the plate down onto the sensor, which will undergo deformation and record a change in capacitance that can be converted to force.

At first, machine screws with screw thread from top to bottom were used to connect the plates. It was noticed however, that the top plate was not efficiently pushed through the screws because the screw thread created a high coefficient of friction between screws and plate. Instead, machine bolts with no screw thread at the top 2 cm were chosen. To further reduce friction between bolts and plate, the bolts were lubricated with Super Lube® Multi-Purpose Grease (Super Lube, New York, USA). To prevent the bolts from sticking out of the device they were shortened approximately 1.3 cm using a band saw.

As some riders pull up the pedal during cycling (Mornieux, Stapelfeldt, Collhofer & Belli, 2008), 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 the top plate. The bolt was then tightened to create a pretension in the sensor. When pulling the device, the top plate could then be pulled upwards relieving the sensor of tension.

The total weight of the device is 221 g, with a height of approximately 1.8 cm. The device is pictured in figure 1A and B.

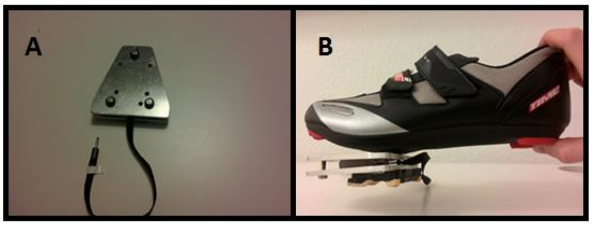

Figure 1: Illustration of the device seen from above (A) and mounted between a cycling shoe and cleat (B).

In order to test the validity and reliability of the device, it was compared to a force platform which was considered the golden standard. The device itself cannot be mounted to the force platform. Instead, an aluminium plate was attached to the center of the force platform using four clamps. The device was attached to the aluminium plate using four countersunk machine screws. The experimental setup can be seen in figure 2.

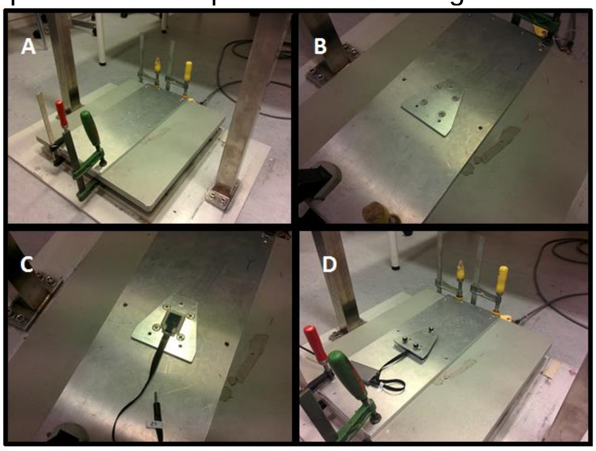

Figure 2 illustrates the experimental setup. At first, an aluminium plate was attached to a force platform (A). The bottom part of the device was then tightened to the plate (B), before the sensor was positioned in the center (C). Finally, the top part of the device was tightened to the bottom part (D).

Data from the PolyPower sensor was recorded and sampled at 50 Hz using sensor software (Wireless Sensor Controller, Danfoss PolyPower A/S, Nordborg, Denmark).

The vertical (Fz), anterior-posterior (Fy) and medio-lateral (Fx) ground reaction forces and the corresponding reaction moments (Mz, My, Mx) were recorded and sampled at 2000 Hz

by a force platform (AMTI, OR6-7, Watertown, MA, USA) and amplified with a gain of 1000 (AMTI, MCA-6, Watertown, MA, USA). Specific software (Mr. Kick III, Aalborg University, Aalborg, Denmark) was used for data recording and low-pass filtering (second-order Butterworth).
The experimental protocol consisted of pushing and pulling the device manually with both short, long, powerful and soft pushes and pulls, and in different directions. The dynamic push test and pull test lasted 2 minutes each.
The device was pretensioned with a force of 37.57 N. The total force applied to the device was at all times kept under 294.20 N, as this was the maximal amount of stress the sensor had been applied in testing by the manufacturer.
Data from the PolyPower sensor and the Fz force component from the force platform were analysed using MatLab (R2014b, The MathWorks, Mass., USA). Data from the force platform was downsampled to 50 Hz to enable comparison, and data from the sensor was low-pass filtered (second-order Butterworth). Comparison of the device and the force platform in the experimental protocol was investigated using Bland-Altman plots, which has been described as the best way to measure agreement between two different methods of measurement (Bland & Altman, 1986). The plots were made using Statistical Package for the Social Sciences (SPSS v22.0, SPSS Inc, Chicago, USA).

RESULTS: Bland-Altman plots (fig. 3 A, B) illustrate the between-device differences for the calculated Fz.

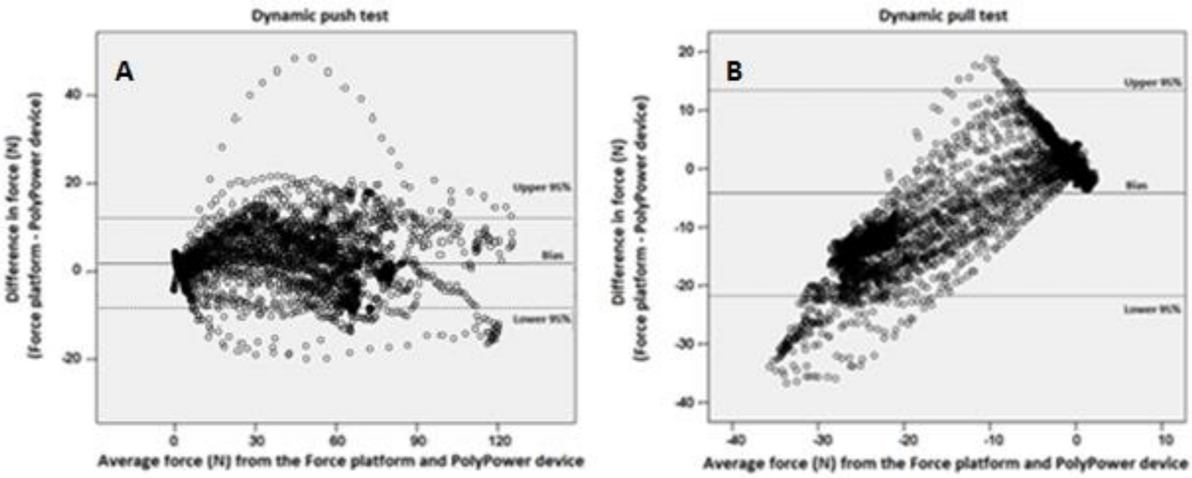

Figure 3: Bland-Altman plots of the between-device differences in the dynamic push test (A) and pull test (B) for the measured Fz force.

In the dynamic push test, the bias was 0.50 N, the upper LoA 10.44 N and the lower LoA −9.44 N, see fig. 3A. In the dynamic pull test, the bias was −4.14 N, the upper LoA 15.56 N and the lower LoA −23.84 N. A clear tendency of the PolyPower device measuring lower than the force platform at more negative average force can be observed (Fig.3B).

DISCUSSION: The main purpose of this study was to develop and produce a device capable of measuring pedal forces using a PolyPower force sensor. This was accomplished by placing the sensor in between two plates capable of pushing down onto the sensor when a force was applied. This construction has the ability to be mounted between a cycling shoe and cleat, and measure Fz forces.
When pushed upon, the device produced similar Fz forces to a golden standard force platform, as a Bland-Altman plot showed a bias, upper LoA and lower LoA close to zero. This indicates that the device is valid and reliable when measuring positive Fz forces. The

dynamic pull test revealed a tendency for the device to underestimate the pulling force. To enable force measurement when pulling, rubber washers were inserted between the head of the bolts and the plate, and the device was pretensioned. This construction does not seem to have been successful, most likely due to the elastic properties of the rubber washers. When pulling the device, some of the force will be used to compress the rubber washers and will be transferred to the bolts. A possible solution to this problem could be to determine the elastic properties of the washers in a compression test and adjust for the fact that not all of the force is going through the sensor, so to speak.

The sensor exhibits a slow recovery rate and as a result, the PolyPower device will begin and end each cycle measuring a higher Fz force than the force platform. The slow recovery rate of the PolyPower force sensor is likely due to the viscoelastic nature of the material. 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 device.

The uniqueness of the device developed in this study compared to other devices capable of measuring pedal forces, is its ability to be mounted between a cycling shoe and cleat, and potentially act as a wearable power meter. Commercially available power meters require to be mounted on the rear hub, crank or pedal for example. If a user has several bikes 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 bike to another. This 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 rider and not the bike.

A constraint in this device is the measurement of solely Fz forces. If the device is to be used as a power meter or to calculate the index of effectiveness, Fx should also be recorded, as this force component contribute to bike propulsion as well (Bini, Hume, Croft & Kilding, 2013).

Furthermore, in order to measure power and index of effectiveness, angular sensors for pedal kinematics assessment should be added to the device. Angular sensors are necessary to decouple effective force from total force applied to the pedal since the pedal coordinate system does not follow crank or global coordinate system.

CONCLUSION: A device, with the ability to be mounted between a cycling shoe and cleat, and measure Fz forces using a PolyPower force sensor, was developed. Compared to a golden standard force platform, the device appeared valid and reliable when a force was applied. Some limitations were recognized, such as a slow recovery rate for the sensor and an inability to measure pulling forces correctly. Furthermore, in order to be used as a power meter or to calculate index of effectiveness, the device should be capable of measuring Fx forces and use angular sensors for pedal kinematics assessment.

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