Chapter 2
Measuring Pedal Forces

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2.1 Introduction

Bicycle components have changed over the years in order to minimize resistive forces and energy cost for pedaling with purpose of maximizing cycling performance [1]. Along these lines, the assessment of forces exerted by cyclists is important for the analysis of pedaling technique and to anticipate injury risk factors.

Cyclists continuously aim to produce maximal possible power output for longer duration, particularly when power delivered to the cranks can be translated into bicycle speed. To ascertain the optimal transfer of forces applied to the pedals to cranks, the measurement of pedal forces and pedal motion is critical for the development of interventions with focus on increasing maximal crank torque. An alternative approach is to define a given speed (or power output) and to seek for alternative ways to minimize peak crank torque and pedal forces in order to maximize the use of pedal force application.

During the last two decades, various instruments have been developed to provide force measurements [40, 75, 76]. However, most of these devices were limited to the laboratorial environment. A recent device has been presented in order to enable measurements during track cycling [77]. In line with that, commercial systems developed instrumented pedals to provide wireless measurements

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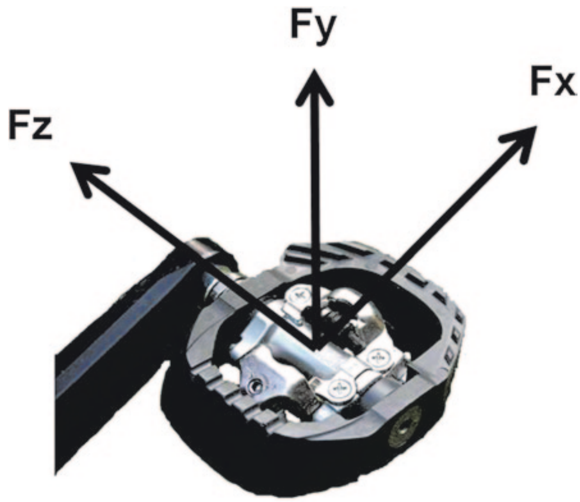

Fig. 2.1 Illustration of three-dimensional components of the force applied to the pedal surface *Fx* anterior-posterior, *Fy* vertical, and *Fz* medio-lateral

during outdoors pedaling exercise (http://www.polar.com/en/about_polar/news/Polar_and_LOOK_launch_together_power_pedals). Despite this, commercial wireless systems may be limited to the assessment of power output rather than actual pedal forces. In this chapter, a description of possibilities for measuring forces and the potential benefit of each component of pedal forces will be presented. Further, pedal and crank kinematics will be introduced to highlight their importance for the assessment of pedaling kinetics and technique.

2.2 Pedal Force Components

Muscle force is transferred to the pedals throughout bones and tendons but the direction of force application on the pedals depend on the position of the foot in relation to the pedal surface. For the analysis of force directions on the pedal surface, total (or resultant) pedal force is separated into three orthogonal components (normal—Fy, anterior-posterior—Fx and medio-lateral—Fz), as shown in Fig. 2.1.

Only normal and anterior-posterior pedal force components can be translated into crank torque depending on the position of the pedal in relation to the crank. This helps to explain why most studies focused only on the measurement of these two force components. Another reason could be associated with the increase in complexity from electronic settings when the medio-lateral force is measured along with rotation moments on the three-dimensional axes of the pedal. However, research has shown that increases in lateral force application on the pedal surface [78] and larger internal rotation moment along the Fy axle [79] could be associated to overload on the knee joint soft tissues [66].

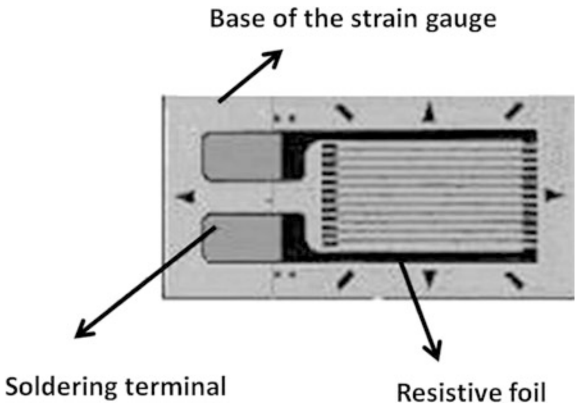

Fig. 2.2 Expanded view of a commercial strain gauge element for strain measures

2.3 Principles of Force Measurements in Instrumented Pedals

The most common approach to measure forces applied to the pedals is by measuring the deformation on the pedal structure resulting from force applied to the material. This principle follows Hook's law, where a linear deformation is expected when force is applied at a constrained bandwidth. Whenever force application exceeds the elastic properties of the material, permanent deformation is observed and changes in force to deformation relationship are observed.

Strain gauges are the most used sensor in pedal force measurements due to their low cost and easy handling compared to other sensors (e.g., piezoelectric crystals). Strain gauges are attached to areas on the material where larger deformations are expected, commonly simulated using finite elements modeling [80]. In Fig. 2.2, an example of strain gauge is shown with illustration of components of the sensor. Once strain gauges are attached to the material, deformation from force application on the material is transferred to the strain gauge, which changes the resistance on the foil structures. For a given current level passing to the foil, changes in the structure of the foil will affect voltage output due to changes in electrical resistance. Therefore, net changes in voltage (input to output) will be linked to the force applied to the material. In Fig. 2.3, an instrumented pedal is shown with strain gauges attached to the pedal spindle.

2.4 Historical Changes in Methods for Force Measurements

Faria and Cavanagh [82] reported that in 1889, R.P. Scott was the first to perform measurements of the force applied to the pedals. Guye [83] also described that R.P. Scott used a mechanical device that, similarly to the one presented by Sharp [84], enabled small blades to draw on paper whenever force was applied to the

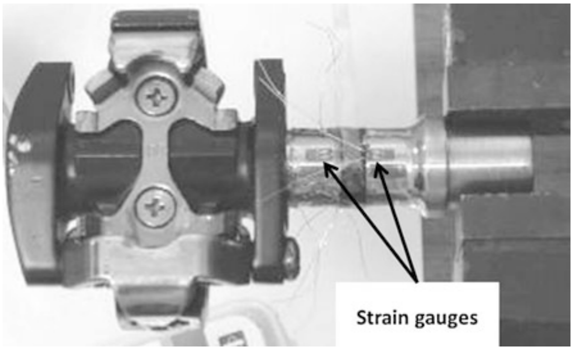

Fig. 2.3 Strain gauges attached to the pedal spindle [81]

pedal. Assuming a linear relation between the force applied to the size of drawing on the paper, the magnitude of forces could then be quantified. However, at that moment, only the normal force component (Fy) was measured. This limitation was latter addressed by instrumented pedals introduced by Dal Monte et al. [85] that enabled bilateral measurements of normal and anterior-posterior pedal forces during stationary cycling in the laboratory.

In the early 1980s, the first three-dimensional pedals were presented [40], which provided full assessment of loads produced during cycling. At that time, attention was given to the relationship between magnitude and direction of pedal forces [40] and to the potential risk of development of overuse injuries in cycling [66, 78, 86]. The knee joint was the focus due to larger lateral pedal force during cycling with more medial position of the knees [78] and larger internal rotation moment along the Fy axle for injured cyclists [79].

Another avenue is the assessment of the percentage of the force applied to the pedals that drives the crank. The index of effectiveness is the traditional analysis of the percentage of use of pedal forces that produce propelling power on the bicycle, and it can be measured as the ratio between the impulse of the effective force (i.e., force perpendicular to the crank) and the total pedal force (see Eq. 2.1).

$$\mathrm{IE} = \frac{\int_0^{360} \mathrm{EF}\ \mathrm{d}t}{\int_0^{360} \mathrm{RF}\ \mathrm{d}t} \tag{2.1}$$

Index of effectiveness (IE), computed by the ratio between the impulse of the effective (EF) to the resultant (total, RF) pedal force (RF) [87].

In Fig. 2.4, components from resultant pedal (RF) force in sagittal plane are shown, as normal (Fy) and anterior-posterior (Fx) along with the effective force (EF), which states for pedal force applied perpendicular to the crank.

Most studies assessing pedal forces were limited to road cycling. In the late 1990s, instrumented pedals were customized for mountain bike riders [88]. That involved the adaptation of cleat system to SPD Shimano, rather than the road

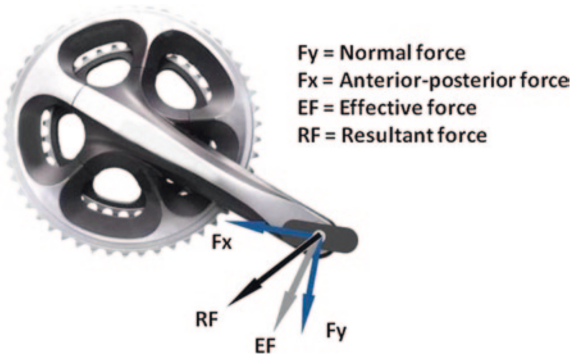

Fig. 2.4 Illustration of pedal force components in sagittal plane (*Fy*) and anterior-posterior (*Fx*) to the pedal surface along with the effective force (*EF*), which stands for the percentage of resultant force (*FR*) that is acting perpendicular to the crank

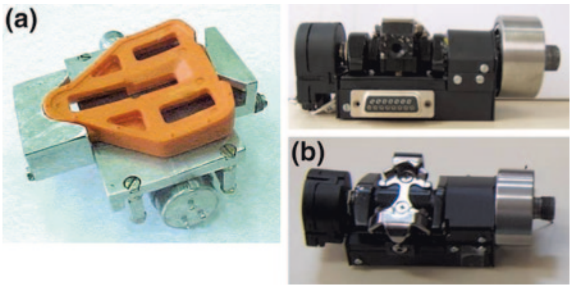

Fig. 2.5 Instrumented pedals designed for measurements of normal (*Fy*) and anterior-posterior (*Fx*) components of pedal forces. **a** Instrumented pedal for Look-Delta cleats [89], commonly used by road cyclists and triathletes. **b** Instrumented pedals for SPD-Shimano cleats [81], commonly used by mountain bikers

Shimano or Look type cleat, which are often used in road cycling and triathlon. Along with limitations on the use of most instrumented pedals to laboratorial environment, limited cleat types were observed. In cycling, cleats vary among brands and exchanging cleats involves changing cleat to shoe position and sometimes changing type of shoes. In Fig. 2.5a, we introduce an instrumented pedal force system developed in our university [89] and used in various studies from our research group [30, 45, 90–92]. This system was designed for Look-Delta cleats. In Fig. 2.5b, a second instrumented pedal force system was designed by our research group to provide measurements of forces using SPD-Shimano cleats, commonly observed in mountain bikers [81].

Throughout the years, different prototypes were presented in order to provide an alternative to instrumented pedals. The first prototype with a different design was based on the attachment of a cycle ergometer to a 3D force plate [93]. In that project, forces were determined using inverse dynamics of the bicycle and force plate connection. That enabled cyclists to use their own pedals, which improved instrumented pedals design.

A second approach was based on the development of an adaptor between the pedals and the cranks [94]. This system provided normal and anterior-posterior force measurements in the adaptor, which were linked to forces applied to the pedals. Again, the main benefit was the possibility for cyclists to use their own cleats and shoes.

A great challenge for research on cycling biomechanics is the ecological validity of measurements taken in laboratorial environment. Indeed, differences in pedal forces have been observed when pedaling on a fixed cycle trainer to cycling on a treadmill [46]. To address this issue, Dorele fellows [77] introduced a partially wireless system that enabled measurements to be taken during track cycling. An analogical to digital converter was carried by the cyclists on a backpack, and signals were then wirelessly transferred to a computer sitting in the center of the track. With this device, coaches and biomechanics could either save data for off-line analysis or could process data with minimal delay between acquisition and decision-making.

Improvements in automation and data transferring technology largely impacted progress in force measurement systems. Wireless technologies are developing fast and will be the main avenue to enable more ecological assessments of cyclists and triathletes of different disciplines. On the other hand, high cost still limits a wide spread of this technology to varying levels of cycling (from recreational to professional). At the moment, commercial systems are slowly appearing in the market. Instrumented cranks were adapted to provide crank torque measurements outdoors [95]. However, they have been shown to limit the assessment of force exerted by each leg [96], which limits any analysis of asymmetries in cycling.

2.5 Angular Sensors for Kinematics Assessments

Exclusive measurement of pedal force components can be incomplete if pedal kinematics is not provided. To decouple perpendicular to resultant pedal force, information on crank position and pedal angle is required because pedal coordinate system does not follow crank or global coordinate system (Fig. 2.6). In Fig. 2.6, it is possible to observe that pedal inclination (θ) changes Fy force orientation. Therefore, measurements of pedal inclination are critical to decompose Fy and Fx from the pedal to the crank and/or global coordinate systems.

Two methods are commonly used to assess pedal inclination. The first involves filming cyclists pedaling using either one or more cameras. That sometimes involves long time for tracking markers and off-line synchronization with pedal force data. A second approach uses angular sensor (e.g., encoders or potentiometers) attached to pedal spindle tracking rotation of pedal axle in relation to the crank motion. Calibration procedures permit converting changes in voltages in changes in angles during cycling motion. This approach is beneficial because signals can be directly synchronize with force data and because processing time is largely reduced.

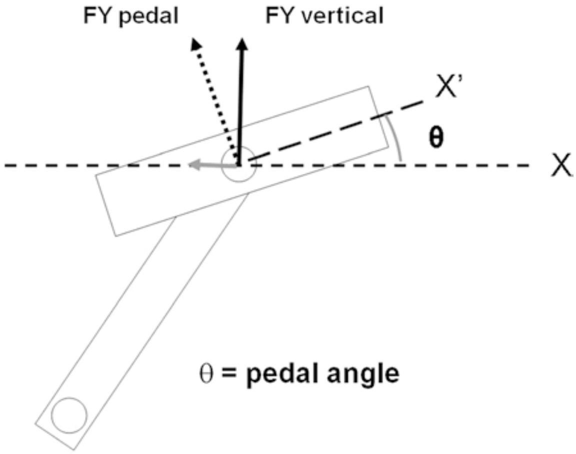

Fig. 2.6 Illustration of the pedal to global coordinate system force decomposition using the pedal angle (θ)

2.6 Sources of Errors in Pedal Force Measurements

Static calibration of loads is necessary to ascertain on the voltage to load relation of each pedal force system. For that purpose, known loads are applied to the X and Y axes of the pedal surface or pedal spindle (Fig. 2.7). Using force data (in volts) collected during this calibration procedure enables users to correct and update calibration factors of instrumented pedals using angular inclination of linear regression taken from voltage (independent variable) to load (dependent variable).

In order to gather accurate force measurements, three main sources are usually referred. The first, as previously described, results from errors in calibration of forces during static load tests. The second is the possible cross talk between orthogonal force components when force applied is aligned to a given pedal axis. A third source is the drift in pedal force measured throughout time. Most of these can be minimized or mathematically amended.

As shown in Fig. 2.7 inset, the control of pedal inclination is critical to contain load application within the Fy axis of the pedal. Any changes in load direction will affect voltage readings and will compromise the calibration procedures. In addition to that, cross talk is commonly observed in single axle force application. This phenomenon can be observed when, as per the example given in Fig. 2.7, load is applied at a single axis, but changes in voltage are also found in other components (e.g., Fx). In principle, assuming that line of force direction is controlled, Poisson effect, which involves the changes in form of a volume when load is applied, is the key explanation. Following the concept introduced by Siméon Poisson, whenever a material is compressed in one direction, an expansion is observed in other directions. In the example provided in Fig. 2.7, compression resulting from load applied at the Fy axis will expand the pedal toward the Fx axis (in minimal dimension) and will be gathered by sensors related to Fx deformation readings. Cross-talk correction has been used for 2D [94] and

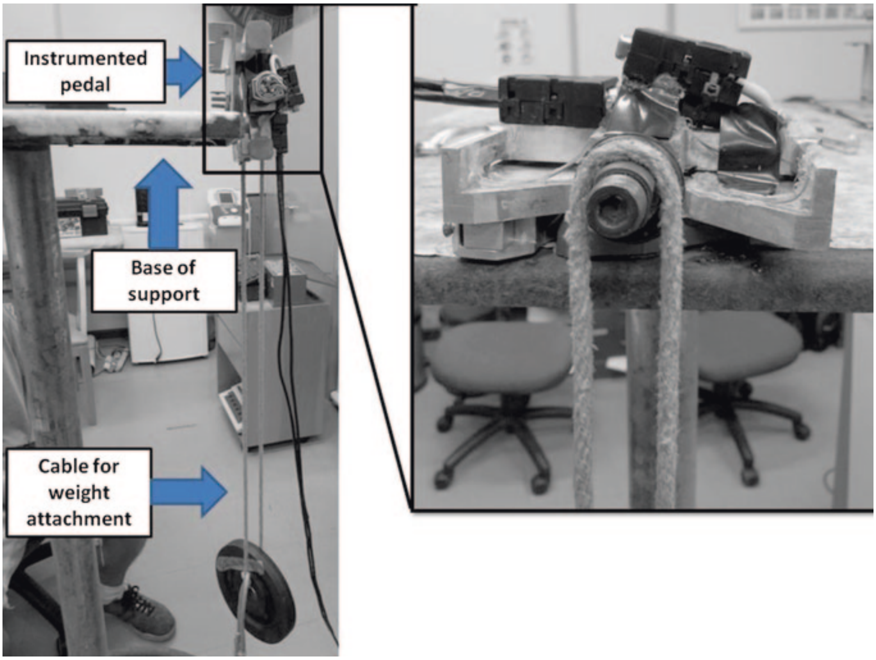

Fig. 2.7 Illustration of a static load calibration procedure using a 10-kg load attached by a rigid cable to the pedal spindle in X and Y pedal coordinate system, ascertain for no pedal inclination

3D force components [80], which enables the compensation on calibration factors for unwanted changes in force readings.

A third effect is drifting in force readings, which have been only reported by Stapelfeldt and co-workers [94]. In this study, changes were −0.02 N/min, which were considered minimum. Strain gauges manufactures recommend that warming up gauges by 20–30 min with power supply and no load application to the material could be a solution to minimize temperature effects on force readings. Taken together, the control of calibration procedures, cross talk and drifts could largely improve accuracy in force measurements.

2.7 Conclusions and Practical Applications

Assessment of pedal forces can provide cyclists and coaches outcomes from changes in pedaling technique along with the possibility to monitor force exerted by cyclists in various pedaling actions. Pedal force measurements have been preferably conducted in laboratorial environment due to limitations in carrying data analog systems and in transferring data for storage systems. Linking pedal forces to measurements of cycling motion (via kinematics assessment) is key to determine further variables related to biomechanics of lower limbs during cycling (i.e., joint kinetics). At the moment, a few commercial systems offer measurements of force and/or power produced at each pedal, which enables the use of force measurements during cycling motion at the clinical and training environment.

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