# A Gage for Measuring Pedal Forces on a Stationary Bicycle

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By

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#### Abstract

We investigated, created, and tested a device used to measure the pedal forces on a stationary bicycle. Such devices have uses in the medical, biomechanical, and sports sciences. This study encompassed researching previous devices to determine the most effective technique, building a device capable of retrieving useful data, and testing the device in a live experiment with human test subjects. Initial research found that most previous designs created pedals that could measure forces with high precision, but usually involved costly components or bulky computers. The primary focus on the experimental design was to create an effective device that not only took force measurements, but that was small enough that it could be incorporated into a non-stationary bicycle and low cost enough that it could be reproduced easily and available for larger studies.

# Acknowledgements

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# **1** Introduction

The first bicycle was invented in 1817 by Baron Karl von Drais, but differed greatly from any modern bicycle by its lack of pedals or any power system. Pedals were added in 1865 by a French inventor named Pierre Lallement [1]. Since then, the bicycle has evolved to become the most efficient transportation vehicle currently available. This has made it a popular item in exercise, as well as a useful tool in scientific studies. This particular study will investigate and create a device to measure the forces applied by a rider to the pedals of a stationary bicycle. It will also take into account making a lightweight, compact, and cost effective design.

The major components of a bicycle are numerous, but this study will be limited to the components closely related to the pedals and the parts of the pedals themselves. On both stationary bikes and over ground bikes the pedal contains a spindle, which is the axle that the pedal rotates around. This usually contains bearings and is inaccessible because it is covered by the pedal body. The pedal body is the casing of aluminum, steel, or plastic, that comes into direct contact with the rider's shoe. Some pedals, like the one involved in this study, also have an attached toe cage, which allows the rider to apply not only downward force on the pedal, but to also pull up on the pedal. The pedal spindle is also attached to the crank arm, the lever arm that connects the pedal to the axis of the bike. The crank arm is then attached to the bicycle's frame and allowed to rotate on bearings.

As the pedal goes through one revolution there are four distinct positions or ranges that it goes through. These ranges are the two dead spots, the forced phase, and the recovery phase. The dead spots are located at the top and bottom of the pedal cycle.

They are termed dead spots because usually a very small driving force is applied to the pedals at these locations. The forced phase is the range from when the pedal leaves the upper dead spot to when it reaches the lower dead spot. This is called the forced phase because it is the time when the majority of the force is applied to the pedals. The recovery phase is the remaining 180° from the lower dead spot back to the upper dead spot. During the recovery phase, some cyclists do apply a driving force by lifting the pedal, but many studies have found that the average cyclist actually only slightly unweights the leg during recovery and allows the pedal to force the leg up [2].

# **2** Applications

The need for an accurate and effective apparatus for computing the pedal forces on a stationary bicycle has found uses in several fields. In the medical field the study of pedal forces has been used to improve physical therapy practices. Furthermore, in the world of cycling, pedal forces can be used not only to improve an individual's technique, but also to determine the loads put onto a bicycle frame and allow manufacturers to produce higher quality frames [3]. Lastly, bicycle ergometers and dynamometers are used in the fields of kinesiology and biomechanics to determine how the muscles of the legs and lower trunk work in tandem to produce the movements and forces we use in daily activities [4].

In the medical field, the use of pedal forces can be used in many sports medicine and stress testing studies. One such example is the study by Bundle et al. [5] that used pedal forces to determine the biologic pathways for maximum human force output at and beyond fatigue levels. This experiment relied on instrumented pedals to obtain measurements during sprint exertion to determine the rate of fatigue of cyclists. The study was able to show a link between the fatigue of maximum pedal forces and the metabolic rates of ATP use and synthesis within muscle fibers. This study helped biologists and doctors better understand how ATP, oxygen, and glucose are regulated within muscle cells.

Pedal forces have been used to calculate work loads of a cyclist for training purposes. A commercial product, called the SRM uses strain measured on the crank and in the crank to chain ring connection to determine driving forces and power output. This device has been used by Lance Armstrong and many other professional, amateur, and

recreational cyclists to measure driving forces. Such information can allow a cyclist to improve form and efficiency. The SRM currently retails for \$2,300 - \$4000 [6] depending on the model and accuracy desired.

The use of pedal forces has been most prominent in the field of biomechanics, where knowledge of pedal forces can be combined with muscle electromyography to show the relationship between muscle action and force output. One such study [7] examines both of these values during variable surface inclines and body positions. Pedal forces can be used to not only determine the muscular forces, but also the direct work output and energy expenditure of a rider. The combination of pedal forces with other data sources such as electromyography or leg kinetics and kinematics has been central in many biomechanical studies.

# **3 History**

#### 3.1 Nomenclature

The following nomenclature follows that of the Newmiller et al. (8) and is used for the discussion of the experiment. The coordinate system can also be seen in figure 1.

x, y, z	local pedal coordinate system
x', y', z'	fixed coordinate system
$F_x, F_y, F_z$	forces in the pedal frame
θ <sub>1</sub>	crank arm angle measured from vertical
θ <sub>2</sub>	pedal angle measured from horizontal

#### 3.2 Research into Pedal Design

The measurement of pedal forces was first studied with great detail by M. J. A. J. M. Hoes in 1968 when he developed a system for measuring the pedal forces of a bicycle by measure of strain within the crank itself [9]. His method used a strain gage situated at approximately halfway down the crank arm to measure strain as well as a potentiometer located at the crank attachment. The data was then transferred by brass slip rings. He then proposed that the only forces that mattered were those in the  $F_x$  and  $F_z$  plane. By this method, the off-axis loads in the  $F_y$  direction were considered trivial. These loads could not be calculated with this apparatus, and more importantly their effect on the strain of the crank was left unknown.

The belief that off-axis strain should be considered trivial continued to be held in the scientific community through the 1970's. In 1979 a report was published that used both the "instrumented" pedal defined by Hoes and a record of high speed films to make



theoretical calculations [3]. The findings showed that there were significant discrepancies between the theoretical model and the experimental results. The conclusion as made that the error most likely came directly from errors in the theoretical model to account for forces pushing forward at the height of the pedal stroke or the weight of the foot on the recovery stroke. Attention towards the pedal angle, defined as  $\theta_2$  in figure 1, led to the conclusion that a second potentiometer located at the pedal will be necessary for more accurate calculations. Furthermore, it was hypothesized that the off-axis forces might not be trivial after all.

In response to the conclusions of the film studies, the first six axis dynamometer was developed in 1981 [4]. The six components that this name refers to are the three components of the force and the three components of the moment. This device was primarily located directly underneath the pedal body. This design had six primary objectives which are listed below:

- The six axis load must be measurable with accuracy of  $\pm 0.5\%$ .
- The dynamometer must not interfere with normal pedaling.
- The dynamometer must be installable on a variety of bicycles.
- The dynamometer must produce data in a form convenient for computer analysis.
- The dynamometer fundamental frequency must be 35 Hz minimum.

 Resolution must be within 0.1 Nm for moments, 1 N for F<sub>x</sub> and F<sub>y</sub>, and 5 N for F<sub>z</sub>. In order to fulfill these design requirements, the conclusion was that a dynamometer consisting of 32 strain gages would be necessary to produce a decoupled system. The gages were connected in full Wheatstone bridge circuits. The design is provided in figure 4, which shows the pedal design. Also included is Figure 3, which shoes the design of a Wheatstone bridge circuit. These circuits can contain one, two, or four individual strain gages called quarter, half, and full bridge circuits respectively. The strain gages are laid parallel to each other to measure the same strain axis, and hooked to the same voltage source to produce a greater resistance change during stress. In the case of quarter or half Wheatstone bridge circuits, the remaining strain gage locations are replaced by resistors of equal value.

This design uses 4 strain gages in each bridge circuit to form full Wheatstone bridge circuits, and each number in the figure refers to the location of a circuit. These locations were chosen to mechanically decouple the system so that the three force vectors can all be measured separately. This design required that the bridge circuits each have distinct voltage sources and leads to detect each specific signal. This design also required the presence of two potentiometers. One would measure  $\theta_1$  at the crank-frame attachment while the other would measure  $\theta_2$  at the pedal-crank attachment. This enabled the researcher to distinguish between the rotating (x, y, z) pedal frame and the fixed (x', y', z') frame.

While the 6 component dynamometer produced by Hull in 1981 is sufficient to provide for the criteria necessary for this experiment, it was made in a time of different technology. At the present time the technological leap of the computer and subsequently all materials testing technology, a simpler solution most likely exists. The best example of this is in a study completed in 1996 by Tom Boyd, M. L. Hull, and D. Bootten [10]. While this experiment is based on the same principles as the 1981 experiment of Hull, the additions of technology have simplified it and increased its accuracy. This was done by using shear panel elements to measure strain. A shear panel element (SPE) is a special



strain gage and 3 reference resistors of equal resistance. In the middle is a half bridge which contains two parallel more than one strain gage in a bridge increases the change in resistance due to a strain. In Hull's experiment, full Figure 3: The three different types of Wheatstone bridge circuits. On the left is a quarter bridge which contains 1 strain gages and two equal resistors. On the right is a full bridge which contains four parallel resistors. Having bridge's were used.



Figure 4: The design for Hull's six-axis pedal dynamometer. On the top left is the design for the pedal body. Two full Wheatstone bridges were placed at each letter. On the top right is the placement pattern for each strain gage, labeled 1-8. Notice that strain gages 1-4 are parallel and form one full Wheatstone bridge. The same is true for strain gages 5-8 [4].



Figure 5: The 1981 six-axis pedal dynamometer by Hull. This pedal used 32 strain gages to measure forces on the pedal [4].

design that allows the mechanical decoupling of shear strains acting upon it. This is a very useful characteristic for the experiment in mind. A copy of a SPE is seen in figure 6.

In Boyd's experiment, a measurement for the pedal forces was derived from the strain of the shear panel elements. The experimenter used a half Wheatstone bridge circuits which contain a set of two parallel strain gages and two equal resistors on each SPE to determine the strain. It is important to note that each circuit had to be nearly perfectly aligned in the direction of the principal strain in order to get accurate results. Furthermore, the device was made so that a total of seven SPE's were used. Four elements were used to measure the dominant  $F_z$  force, two elements measured  $F_x$ , and one measured the small forces of  $F_y$ . The SPE's were then combined with a pedal platform, a potentiometer to measure pedal angle, and a crank hanger. The crank hanger was added to allow for a variable pedal position to be possible. Finally, an extensive calibration using pulleys and weights was completed to ensure accuracy. This was completed by producing forces of known magnitudes and directions to determine the accuracy and precision of the device.

#### **3.3 Research Results**

The results of an elastic crank designed study are seen in figure 9. These results only calculate the force perpendicular to the circular path made by the crank arm. This tangential force can be called the driving force. The equation for the driving force can be defined below.

$$F_{driving} = -F(\sin(\theta_1)\cos(\theta_2) + \cos(\theta_1)\sin(\theta_2))$$
(1)

In this equation  $\theta_1$  is still the crank arm angle as measured clockwise from the vertical position.  $\theta_2$  is the pedal angle measured counterclockwise from the forward



Figure 7: The internal structure of Boyd's dynamometer shows the combination of all 7 SPE's. Six of the seven SPE's can be seen, with the four facing in the x direction being used to measure Fz. The seventh is located on the underside [10].



Figure 8: The SPE pedal created by Boyd et al. to measure pedal forces. The crank hanger and encoder are used to measure the pedal angle ( $\theta$ 2). The Dynamometer contains the 7 SPE's, one of which can be seen. In the top of the picture the pedal-shoe interface can be seen [10].

horizontal to the path created by the back half of the pedal. It is important to note that this equation handles forces at all angles and for both positive and negative force values. It also shows that when  $\theta_1$  is greater than 180° and small  $\theta_2$ , a positive F value will actually cause a negative  $F_{driving}$ . This is also true on the range of 90° <  $\theta_1$  < 270° for F. This is important in understanding the results seen in figure 9. During most of the range from 180° <  $\theta_1$  < 360° there is a negative driving force, mostly due to the pedal lifting the leg during the recovery phase of the pedal stroke [2]. Forces on the pedal in any direction not in the x, z plane are also non-driving forces. This means that all F<sub>y</sub> forces are nondriving forces.

Hull's strain gage design and Boyd's SPE design were both capable of measuring the off axis  $F_y$  forces. Results from Boyd's experiment can be seen in figure 10. Here, we can again see that  $F_x$  and  $F_z$  forces are the primary forces, but it should also be noted that  $F_y$  can have values as high as -50 N [10]. It can also be seen that in this particular study the cyclist actually lifted up on the pedal during the recovery phase with a force of approximately 20 N. By applying data extrapolated from the graph to equation 1 at 315° it is estimated that this rider was able to apply a driving force of approximately 30 N during the recovery phase by lifting on the pedals.



Figure 10: The results of Boyd's SPE pedal study. Here it can be seen that Fz and Fx are the main driving forces. The off axis force Fy is low in magnitude [10].

## 4 Pedal Design

After an extensive survey of previous pedal force dynamometers, we began to design a pedal to complete this experiment. Several criteria were considered from previous pedal designs, which were then considered in the overall development of the pedal. These criteria are listed below.

- The pedal force dynamometer must be easy to install on both a stationary bicycle and a normal over ground bicycle.
- The dynamometer must be both compact and lightweight to limit the influence of the pedal's force measurements.
- The level of error should be comparable to previous studies.
- The data retrieved should be easy to understand.
- The total cost of the pedal dynamometer should be less than \$1000.

We evaluated all of the previous pedal dynamometer designs with these criteria to determine the best design. The design for the SPE pedal presented by Boyd et al. can certainly meet all of these requirements, but it is extremely complex and involves the machining of several parts to specifications that are not provided in the journal. Hull's strain based pedal dynamometer is equally effective, and does not involve any extra machining of pedals. As for the crank design provided by the SRM and Hoes et al., this design offers no benefits in comparison to the instrumented pedal, but has several extra difficulties. Namely, it is much more difficult to run wires from a crank based measurement. This would most likely require the use of brass slip rings or costly wireless technology.

For these reasons, we decided that a strain gage based design based off of Hull's six-axis force dynamometer would be adequate to fulfill all criteria. It was also decided that measuring the non-driving force in the y direction would not be necessary in this experiment. This decision was based off of the idea that the results have shown that  $F_y$  is neither a driving force nor large in magnitude. Unlike any previous experiments considered, we decided that the use of a potentiometer or other angle measuring device on the pedal would not be necessary. Instead, the pedal angles  $\theta_1$  and  $\theta_2$  could be measured by the use of a digital video camera. It was also noted that according to the data collected by Cavanagh and Sanderson [11] the total pedal forces are usually in line perpendicular to the pedal angle  $\theta_2$ . This data can be seen in figure 11. This allowed measurements of  $F_x$  to be limited by only measuring forces in the pedal based z direction.

Strain gages are used to measure the amount that a substance bends in reaction to a force applied to it. This measurement is done entirely electronically by measuring a voltage change. A picture of a strain gage can be seen in figure 12. In the photograph, the foil lines running parallel up and down the gage can be seen. When the substance that the strain gage is pasted onto bends, the resistance in this tightly would coil is increased and the voltage across the gage decreases. The following equation demonstrates how strain and the voltage change are related.

$$\Delta V_{o} = -V_{ext} \left[ \epsilon G_{F} \right] / 4 \tag{2}$$

In this equation,  $\Delta V_0$  is the change in voltage measured after a strain is produced,  $V_{ext}$  is initial voltage,  $\varepsilon$  is the strain, and  $G_F$  is the gage factor, which is a conversion factor from voltage change to strain.



Figure 11: Cavanagh and Sanderson's data displayed in a clock diagram. The top diagram represents the average of all riders while the lower diagram is for one rider. In both diagrams the right side illustrates the forced phase of the pedal stroke, and the left side illustrates the recovery phase. Notice that the force is approximately perpendicular pedal. Also, while the above diagram shows that the average rider allows the pedal to lift his or her leg during recovery, some riders apply a lifting force during the recovery phase like the one below [11].





Figure 12: A strain gage with index finger to compare size. A closer inspection will show parallel wires that change resistance when the gage is bent.

## **5** Methods

#### 5.1 Making the Pedal

Our first objective was to find the different equipment necessary to complete the pedal and test it. We purchased pedals at a local bike shop that had three features of interest. One was that the pedal body had to be one continuous piece of either aluminum or steel. The second criterion was that the pedals must be of standard type and size and include toe cages so that they can be used for both stationary and over ground bicycles. The final feature was that the pedals had to have a design that applied most of the stress onto the central axle, which could be accessible to strain gages. A pair of aluminum pedals fitting these criteria was found and purchased, and the pedals can be seen in figure 17.

A stationary bike was provided by the William and Mary Department of Kinesiology by Dr. McCoy. This bike is the Monark Ergomedic 828 E stationary bicycle. A photograph of the ergometer can be seen in figure 14. The bicycle provides for a variable seat height and handle bar orientation, as well as an internal computer that allows cadence, speed, time, and power to be read. It also contains a variable resistance drag wheel that allows the experimenter or rider to change the difficulty and force required to pedal. A free-wheel mechanism within the stationary bike also allows the rider to coast, pedal backwards, and apply forward force just as an over ground bicycle would. Most importantly, the cranks on this ergometer are compatible with standard pedals.

Because one of the criteria for this pedal design was to produce a low cost pedal dynamometer, the choice of a data acquisition module was limited. Most data acquisition

devices made for strain gages cost more than the \$1000 budget for the entire project. For this reason, the Emant Low Cost DAQ was investigated. This device can be seen in figure 13. The specifications were found on the Emant sales site:

• 22 bit Analog Input at 10 Hz sampling.

• Programmable Gain Amplification up to 128.

• Up to 6 inputs, which can each measure 4 strain gages in Wheatstone bridge circuits. [12]

These specifications are all adequate, except for the 10 Hz sampling rate. This sampling rate would only provide six samples per cycle. A more precise sampling rate would be approximately 100 Hz, which is a full order of magnitude greater. However, a closer inspection of the block diagram in figure 15 reveals that the sampling rate can be changed. For this reason the Emant Low Cost DAQ was purchased as the module for this experiment. We made the changes to the block diagram to allow for a 100 Hz sample rate and to include a write to measurement file command. This command allows all strain measurements to be recorded into text file with delimiters that can later be loaded by a spreadsheet.

We chose a strain gage that would bond to the pedal and record accurate strain measurements. The nature of this study requires measurements at 100 Hz, so a dynamic strain gage was necessary. However, because experiments would occur over a period of several minutes to hypothetically several hours, a durable strain gage would also be required. The criteria considered are listed below.

- The strain gage must be able to measure at a frequency of 100 Hz.
- The strain gage must be durable enough to withstand foot pressures
  - 24



Figure 13: The Emant DAQ. This device is capable of measuring up to five different bridge circuits. The right side is connected directly to the wires coming from the strain gage. The left side connects to a USB port on a computer.



Figure 14: The Monark Ergomedic 828 E. This is the stationary bike used for all trials. It includes an internal sensor for work output and pedal rotations per minute.



The gage must be bondable to aluminum and have a temperature coefficient of 13.

- The sensitivity and accuracy of the gage must be comparable to industry standards
- Solder dots or wire leads must be provided to allow easy connection of electronic equipment to the gage.
- The gage type must be purchasable at a variety of lengths to allow experimentation with lengths.
- The resistance of the gages must be 120 ohms.

After consideration of these criteria, standard gages of type EA-13-060LZ-120, EA-13-120LZ-120, and EA-13-240LZ-120 were chosen, where the only difference between these three gages is the gage length. These lengths were chosen to be 0.060 inch, 0.120 inch, and 0.240 in respectively. The choice of an array of gage lengths was based on the fact that shorter gages are better at measuring peak strain at a known location while longer gages can measure strain over a greater area and average that strain.

We followed the Vishay Measurements Group guidelines for gage bonding using the product M-Bond 200 adhesive. These guidelines can be found online at <http://www.vishay.com/docs/11127/11127\_b1.pdf>. The process begins by degreasing the gage surface. This is accomplished by the use of CSM Degreaser and gauze strips. Next, we applied a generous amount of a deoxidizing agent called Conditioner A while abrading with 320-grit and then 400-grit silicon carbide-sandpaper. We followed up this process by applying Neutralizer 5A to remove any excess Conditioner A and wiped the area dry with more gauze sponges. We made markings with a pencil or pen around the bonding area to align the strain gage with. Then, the strain gage was laid down onto the box top and tape was placed over it. When we peeled the tape up, the strain gage

remained attached. We could then tape the strain gage onto the surface. The tape was then partially pulled up to allow the adhesive M-Bond 200 to be dotted underneath. We applied pressure with our thumb for approximately one minute and then let the gage set for another minute. After this, the tape can be peeled away without disturbing the bonded strain gage.

In order to connect the wires to the Emant DAQ and the strain gage, we used lead solder with a rosin core. Due to the small size of the strain gages, and even smaller solder tabs, our technique for soldering evolved throughout the experiment. The best technique involves heating the soldering iron to approximately 550° F. Meanwhile, we applied tape to the area around the strain gage to ensure that loose wires or spilled solder would not allow current to reach the aluminum surface. Finally, another layer of tape was placed on top of the strain gage at all places besides the solder tabs to prevent damaging the gage during soldering. We then tinned the wire tips and solder pencil by applying lead solder. A small drop of extra solder was allowed to solidify on the wire tips. After all of these preparation stages were completed, we taped the wires into place with the small drop of excess solder located directly above the solder tabs of the strain gage. We then applied the solder pencil to the wire until the solder melted and bonded to the strain gage. After approximately a minute the solder joints were tested by attaching to the DAQ to ensure that an electronic connection had occurred. If this was not the case, we were forced to repeat the entire process. If an electronic connection was made, we covered the entire gage with a semi-transparent duct tape for protection and taped the wires into place once again.

We tested the gages on aluminum bars first in order to practice bonding techniques and soldering as well as to determine the best gage length to use on the pedals. We accomplished this by applying strain gages to two aluminum bars. One bar was only a 0.25 inch thick and over three feet in length. With this long and thin bar strain could be visibly observed when a force was applied. The other bar was chosen to be of comparable thickness and size to the pedal axle that would be used in the experiment. This bar was 0.5 inch and five inches in length. We took photographs of the two bars which can be seen in figure 16. In both cases, force was applied to the tip of the bar by pressing down or pulling up with our hand. Both bars showed a small amount of voltage drift as well as approximately 1 microstrain of high frequency noise, but we were able to make accurate measurements of strain. Furthermore, testing with different length strain gages showed that if there was a specific point where strain was concentrated, then the use of a shorter length strain gage produced better results. However, when the strain was either spread out over an area or unpredictable, a longer strain gage was more useful. In our pedal, the location of strain was nearly impossible to predict, so we chose to use the longest strain gage of 0.240 inch to ensure the best results.

We now knew that we would be using a EA-13-240LZ-120 strain gage (length 0.240 inch) placed onto the pedal to measure  $F_z$  strain and connected to the Emant DAQ. We first used the left pedal and placed three strain gages on the pedal. Strain gage 1 was applied to a flat surface on the bottom rear of the pedal, strain gage 2 was pasted on the bottom of the main axle, and strain gage 3 was placed on the top of the main axle. We then applied forces to the pedal while acquiring data and found that strain gage 3 was measuring the most strain. We then repeated the process with the right pedal, but only



Figure 16: The strain gages were tested by placing them on bars of aluminum. The top bar was large enough that strain could be visibly seen. The bottom bar was comparable in size and thickness to the pedal body. While strain could not be seen, the gage still registered successfully.



Figure 17: The instrumented pedal. While the strain gages are covered by tape to protect them, the wiring can still be seen. Wires were looped around rope for durability and brought out of the pedal to avoid snagging. The black dots visible were used during video analysis to give pedal position.

applied a gage to location 3. Duct tape was wrapped around the wires to prevent tangling and snagging. We also taped over the top of both pedals to prevent the foot from directly making contact with the strain gages and to protect the solder joints. The finished pedal top and bottom can be seen in figure 17. The wires were then taped to a small cord of rope to further promote durability and prevent damage and then attached to the Emant DAQ.

The circuitry of design of this experiment is seen in a photograph in figure 18 and as a diagram in figure 19. We used the quarter Wheatstone bridge circuit design for this experiment. Reference resistors rated at 120 ohms were used to form the other 3 quarters of the bridge. The channels used were AIN 0 and AIN 2. This left 4 more channels available, which would allow more quarter bridges to be connected. While in the experiment only one pedal was used to retrieve force measurements, it was possible to measure forces from both pedals during the same time.

#### **5.2 Experimental Setup**

Three male subjects were chosen from the William and Mary Cycling Club. Their weights were  $74 \pm 8$  kg and heights of  $1.82 \pm 0.05$  m. The subjects were given approximately 10 minutes to warm up by stretching and riding on the stationary bike. We instructed each subject to maintain a cadence of 100 RPM and a power output of 200 watts. Each subject was allowed to freely change the resistance level of the bicycle at will. Once the subject felt adequately warmed up, he was instructed to unload the pedal so that any voltage drift or other offsets could be zeroed out and a zero force level could be defined. The rider was then asked to resume pedaling while data was taken.







Figure 20: The experimental setup with subject from the view of the video camera recording pedal position. The laptop is included in the view to allow the synchronizing of data. The black dots located on the pedal and the rear of the stationary bike will aid in digitizing the pedal and crank angles.

We took data in the form of force measurements from the left pedal only. The decision to only use the left pedal was based off of the idea that pedal forces would be relatively symmetric [13] and that running wires underneath the bicycle would increase the likelihood of snagging and damaging the pedals. We took data for approximately one minute at 100 Hz. Data was recorded into a delimited text file and then converted into a spreadsheet. After zeroing the pedal once again, we asked the rider to balance with one foot on the pedal. This gave a constant strain measurement under the full weight of the rider. Finally, we took the mass in kilograms of each subject on a digital scale with accuracy up to 0.25 kilograms. To gather more data, four extra subjects that were not asked to pedal were asked to give their weights and record static strain measurements. This was done to calibrate the pedal, where the known force due to the weight of the subject could be compared to the strain produced by the subject's weight.

Video was taken of each subject's leg positions during the pedaling portion of the trial. We were able to use a Panasonic 500 Mini-DV camera and a tripod on loan from Swem Library's Media Center. Markers placed on pedal body and crank could be used in comparison to markers placed on the fixed frame of the bicycle body to produce pedal and crank angle data for  $\theta_1$  and  $\theta_2$ . The computer used to log data during a trial was also placed in the camera's frame of view to aid in the synchronization of data. Synchronization was further aided by reading off time markers audibly to the camera. The camera's point of view can be seen in figure 20, which is a photograph taken from the video camera. Maxtraq software was then used to digitize these markers, calculate the angles, and synchronize all the data.

# **6 Results and Analysis**

We collected data in the form of strain measurements from the Emant Low Cost DAQ and in the form of angle measurements by a video camera observing the pedal and crank angles. The original strain results for subject 1, 2, and 3 can be seen in figures 21, 22, and 23 respectively. Subject 1 had two clearly defined force peaks. The larger first represents the driving force, while the second and smaller peak is the force exerted on the pedal during recovery. This force is a negative driving force. Subject 2 had a much smaller second peak, which represents a smaller recovery force. Subject 3 had results similar to subject 1.

Video analysis by means of Maxtraq software allowed digitization of angular kinematics data for  $\theta_1$  and  $\theta_2$ . We obtained these values at a frame rate of 30 frames per second. Averaging was used to increase this frame rate to 100 frames per second in order to match it to the strain data. The angular data can be seen in figures 24, 25, and 26 for subjects 1, 2, and 3 respectively. A linear fit for the crank data was taken to give angular velocity. The three subjects were within 40 degrees per second of each other with this measurement. For subjects 1 and 2, pedal angle versus time gave a wave pattern, whereas subject three had a much more irregular pattern for pedal angle.

Results were processed to correct for the irregularities caused by voltage drift and voltage offset. Voltage drift was found to by the long range linear plot of several crank revolutions. For subject 1, we found that a 3.002 microstrain per second drift in the results occurred. The data was corrected based off of this calculation. The respective drift coefficients for subject 2 and subject 3 were -2.384 and 0.007 microstrain per second. Voltage offset was originally reset by zeroing the apparatus before each trial, but

this still allowed offsets of up to 50 microstrain to be found in the results. Subject 2's original strain data seen in figure 22 is an example of this. Clearly, the subject did not constantly apply a negative force during the trial. To account for this shift, information from previous studies such as those seen in figures 9, 10, and 11 were used to zero the strain measurements to the origin. The actual offsets used were +19.2 microstrain, -50.0 microstrain, and +100.7 microstrain for subjects 1, 2, and 3 respectively.

We also analyzed each subject's data to combine the data from the angular measurements and the strain data according to the common time axis and to convert the strain data into forces. Data was synchronized using the video images, and then combined by using the time data. This provided data in the form of pedal strain, pedal angle, crank angle, and time. Force was calculated by a calibration coefficient. This coefficient was found from rider's weights in Newtons and subsequent strain, as was described in the methods section. A graphical representation of this relationship can be seen in figure 30, which shows the linear relationship between forces applied to the pedal and the strain that was recorded. This relationship was found to be 0.1566 microstrain/Newton. The equation for all of the conversions made is seen below.

$$F = (\varepsilon + Dt + \chi)/(k)$$
(3)

In this instance, F is the perpendicular pedal force in the negative z direction of the pedal frame, t is time, D is the drift coefficient found for each subject,  $\chi$  is the offset strain, and k is the force-strain coefficient found to be 0.1566 microstrain/Newton. We then used this F in equation 1 along with the pedal and crank angles to find the driving force.

Figure 27 shows the driving force versus the crank angle for subject 1. This subject had a maximum force of 376.0 N at a crank angle of 106°. The subject also had a negative driving force during the range of 250° to 10° with an absolute minimum driving force of - 149.9 N at 302°. Figure 28 graphically represents the driving force versus crank angle for subject 2. Subject 2 had a maximum force of 323.9 N at 84.7° and a minimum force of 68.7 N at 221.7°. This subject also had a positive driving force versus crank angle can be seen in figure 29. The third subject 3's data for driving force of 447.5 N at 98.5° and a minimum force of -171 N at 335°. This subject also had a negative driving force during force during the recovery phase lasting from 270° to 25°.







Figure 22: The data output from the device for subject 2. Notice for this subject, the recovery peak is much smaller. This data had to be transformed by the same processes as mentioned for subject 1.







Figure 24: The crank and pedal angles as measured for subject 1. These measurements were taken from video taken of the angles. A linear relationship representing angular velocity was found for the crank angle. The pedal angle followed a wave pattern. This data was used to calculate driving force.



Figure 25: The pedal and crank angles for subject 2 as seen from a video camera. Again, a linear relationship is observed for crank angle, with a slope representing angular velocity. The equation is provided on the graph. This data was used to calculate driving force.



Figure 26: The pedal and crank angles for subject 3. Notice that for this subject the pedal angles did not follow a wave pattern as closely as it did for the other subjects. Again, an equation for the linear pattern of crank angle is provided.



Figure 27: The driving force calculated for subject 1. This subject had a peak driving force of 376.02 N. We found that in the range of 250° to 10°, the subject applied a negative force. This is during the recovery phase.



Figure 28: The driving force calculated for subject 2. This subject had a peak force of 323.94 N. This subject also reached his maximum driving force at an earlier angle. Finally, this subject also applied a positive driving force by pulling up on the pedal during the recovery phase.







Figure 30: The subjects' weights, along with several non-pedaling subjects' values, were used to calibrate the pedal's strain force relationship. The linear equation showed that every Newton of force would cause 0.1566 microstrain. The r-squared for this relationship was 0.9885.

## 7 Discussion

#### **7.1 Experimental Results**

Data collected from the three subjects can be compared to past results, such as those seen in figures 9, 10, and 11. It can clearly be seen from these results that the instrumented pedal was effective at measuring forces. Figure 9 gives the best comparison for force data, as this figure is also in terms of driving force (or perpendicular force) per crank angle. Much like the results of this crank-based strain measurement, our pedal measured peak positive driving forces to be approximately 4-6 times greater than the absolute value of the negative driving force during recovery. Also, peak forces were in a comparable range to previous studies, even though they were variable. Subject 1, 2, and 3 had peak driving forces of 376.0 N, 323.9 N, and 447.5 N respectively. In comparison, B. J. Fregely and F. E. Zajac's study [2] found a peak driving force of approximately 300 N and P. R. Cavanagh and D. J. Sanderson [11] found an average driving force of approximately 350 N, with some cases greater than 600 N. It is clear from these differences in data sets that differences of less than 100 N between all subjects has not been unusual in previous studies.

The three individual subjects also showed at least two very different pedaling styles, which the device was capable of differentiating between each. Subject 1 pedaled with a downward force on the pedal at all times. This produced a positive driving force from the range of 15°-215°. At first it seems counterintuitive that a force in the negative z direction would produce a positive force during the recovery phase. While this is true, this conclusion must be compared with pedal angle data. It can clearly be seen in figure 24 that as the crank angle passes through 180°, the pedal angle is decreasing to angles of

130° and lower. This is because subject 1's foot is in plantar flexion during this period. Plantar flexion refers to the increase of the angle between the ankle and the top of the foot. This high level of plantar flexion allows for the rider to continue pushing the pedal through the "dead spots" at 180°. This rider continued to keep his foot in plantar flexion, which may explain the larger negative driving force during recovery. Furthermore, we can see that the rider's maximum force was measured at a crank angle of 106°, not the 90° expected. However, upon closer examination of figures 9, 10, and 11, we see that this is not unusual either. This offset from horizontal will be discussed later.

Subject 2's driving force data has one unique characteristic, which is that during the recovery phase subject 2 applied a positive driving force. Another important characteristic is that this subject had a maximum force located at 82° and before 90°. Both of these characteristics can be seen in figure 28. Similar characteristics can be seen in the lower clock diagram in figure 11. Here, Cavanagh and Sanderson report a recreational rider that applied a maximum force prior to reaching the horizontal riding position, and the same rider also pulled up during recovery to have a net positive driving force during this period. We completed an analysis of subject 2's angular kinematics data and observed that this rider had pedal angles greater than 180° during the forced phase and pedal angles less than 180° during recovery. This translates to plantar flexion at the ankle joint followed by dorsiflexion. This characteristic is unique to subject 2 and is not seen in the Cavanagh data. Clearly subject 2 exemplifies a different style of cycling that a small portion of the population must exhibit. Furthermore, the instrumented pedal is able to distinguish between these two noticeably different pedaling techniques.

Subject 3's data much more closely resembles that of subject 1. This subject's driving force dataset is graphically represented in figure 29. The subject had the maximum observed peak force measurement of 447.5 N. The subject also had a negative driving force observed during recovery, with a minimum driving force comparable to that of subject 1. Maximum force also occurred at 98.5°, which is past horizontal. All of these observations are comparable to not only subject 1, but also the mean rider measurements seen in Figures 9 and 11. It is apparent that this pedaling style is the most common observed among cyclists, where there is a positive driving force peak at an angle slightly greater than 90° followed by a negative driving force during recovery. We also observed a less smooth pedal angle graph in figure 26 for subject 3. While the pedal angle ranged from 120° to 170° (the smallest range observed), the pedal angle varies more sharply. This rider also had a pedal angle in the range of plantar flexion at all times.

Figure 31 is included to give an example representation of what a very efficient pedal stroke would look like graphically. While a physically ideal pedal force diagram would be a flat line of force, this is not a biomechanical reality. This diagram was created using patterns observed among the three subjects used in this study. A peak force of 300 N is applied during the forced phase and a driving force of 50 N is still applied by lifting the foot during recovery. While this is still an unreasonably efficient pedal stroke, it is a good reference to compare results to. Still, there is only a small change in total force applied in this pedal stroke and most data suggests that even elite and professional cyclists benefit more from decreased air drag than from increased pedal forces. [11]



Figure 31: An example data set for a very efficient rider. This data was programmed using a maximum peak force of 300 N during the forced phase, a peak force of - 50 N during the recovery phase, and a pedal angle range of motion of 145° (plantarflexion) during the forced phase and 185° (dorsiflexion) during recovery. Notice that there are still "dead spots" of no force located at approximately 0° and 180°. Also notice that the recovery phase's force is still less than the forced phase.

Inconsistencies with previous pedal results and general items of error can also be observed in the results. The most notable was mentioned earlier, which is that the results had to be re-zeroed after data collection due to a voltage offset. The level of re-zeroing is seen in figures 21, 22, and 23. While the pedal was zeroed before each trial, and allowed to equalize by temperature for at least 10 minutes for every trial to minimize voltage drift, the offset was still a problem. We observed that the heat caused by the rider's foot and friction between the shoe and the pedal caused temperature changes that could not be easily eliminated from the pedal strain data. While the relative effects of this strain offset are minimal, we had difficulty determining the absolute zero strain point for each data. This point was determined using previous results from other studies, which is not an entirely objective qualifier. This could explain why such large negative driving forces were observed in the pedal.

Another inconsistency noticed is the voltage drift seen in the results. This drift is most observable in subject 2's data in figure 28, where the strain measurements vary, especially at angles where low force measurements are being made. We can see this best during the recovery phase, where even though the majority of data points are positive, two negative data points are also observed. There are most likely three major causes for this voltage drift. One is that aluminum pedals were used, and aluminum's high level of conduction and convection of heat can cause very small microstrain vibrations within the pedal. Another likely cause is that the Emant Low Cost DAQ is made to run at a sampling rate of 10 Hz maximum. For this experiment, we made the device measure at a sampling rate of 100 Hz, pushing the device's capabilities. During experiments at 10 Hz, the device displayed almost no voltage drift after a ten minute warm-up period. It is

likely that the increase in sampling rate introduced this error. The last possible source of voltage drift is that the device had difficulty making measurements at low forces. This is possible because the highest amount of voltage drift was observed at for the lightest subject that produced forces of the lowest magnitude. Still, it is important to see that the results still closely mirror those of previous studies, so these sources of error are not significant enough to discount the data obtained.

The last sources of error were caused by our experimental mistake. One is always assumed whenever working with strain gages applied by hand. This is called strain gage nonlinearality, which accounts for the slight angular displacement between the strain gage and the intended axis of measurement. While this is always present at some degree, the results obtained do not indicate that this is a significant source of error. Another mistake occurred during camera setup. We did not reduce camera shutter speed to allow more accurate measurements of pedal and crank angles. This produced film images of slightly blurred angles. However, the images were still clear enough to obtain consistent pedal measurements. This error was further eliminated by using signal processing provided in the Maxmate software and by using a crank revolution that exhibited the smoothest pedal angle data. Because only one revolution was needed for each subject, data was always chosen based upon the data set with the least outlying points contained.

The use of pedal angle measurements to calculate total driving force proved to be an important measurement to incorporate in this study. At first, we were surprised to observe such large ranges of motion in the pedal angle, and this pedal angle had effects that were noticeable in the driving forces observed. Subjects 1 and 3 had pedal angles always under 180° and had maximum forces located beyond a crank angle of 90°. In

comparison, subject 2 had a peak force located before horizontal and during this time had a pedal angle greater than 180°. It is likely that these two conditions are related, because an increased pedal angle allows the rider to push in a more forward direction. This would cause an increase in driving force before the crank passes through 90°. In comparison, a pedal angle less than 180° allows the rider to apply a force in the negative x direction, which would increase force after the horizontal position.

While it is impossible to make measurements of the total error of this instrumented pedal without a more complex calibration technique, we can assume that the total amount of error is greater than the 1% goal set forth by some previous experimenters. The primary benefit of our pedal is the low cost and ease of creation of the pedal. Furthermore, the preceding section proves that while small relative levels of error are present, the device is capable of taking useful and consistent force measurements.

#### 7.2 Cost Effectiveness

The total cost for the creation of two instrumented pedals was very low compared to that of previous studies. The best comparison is that of a commercial product called the SRM, which as mentioned before has a total cost of \$2,300 - \$4000 and only takes driving force data similar to that taken by the instrumented pedal set forth in this paper. While Boyd et al. does not give a total price for his pedal design, the device included several more strain gages, a more complex data acquisition module, and 7 machined metal SPE's. Strain gage data acquisition modules usually range in price from \$300 to over \$2000 for more complex systems. For measurements of more strain gages than the 5-6 measurable by the Emant Low Cost DAQ such as the 32 strain gages measured by

eight different channels by the pedal created by Hull et al., a more expensive module would be necessary. It is easy to see why previous experiments had instrumented pedals and components with a total cost greater than \$2000.

The Emant Low Cost DAQ and a strain converter were purchased for a total cost of \$118. Thirty strain gages for experimentation, cleaning chemicals, bonding chemicals, and special tape were purchased for \$101. Even then, only a small portion of these supplies was actually used during the course of the experiment. A set of aluminum pedals was purchased from a local bike shop for \$15. Silicon Carbide sandpaper was purchased for a cost of \$4.35 and a mini DV for the video camera cost another \$15. The video camera used in this experiment was borrowed at no cost from Swem Library, as was the case for the Monark Ergometer. There was no need to purchase any software because the Emant DAQ was compatible with Labview. We had a total expense of \$253.35 for the experiment. This can be assumed to be a full order of magnitude less than previous pedal designs.

Size and weight are also important considerations if we consider applying our pedal design to overland bicycles. The device in its current form could not be applied to a typical moving bicycle because it is required to attach to a laptop. If a Data Acquisition Module that used a data stick within the pedal that could later be connected to a PC, then this design could immediately be implemented into overland bicycles. The weight of the pedal, even including the Emant DAQ is very small. Strain gages and their subsequent wiring have a mass that is negligible for anyone except elite cyclists. This would mean only the DAQ and processing computer would significantly increase weight. The DAQ in its current form weighs less than 200 grams. The major characteristic that requires this

device to be used only with stationary bicycles for now is wiring. Again, if this could be avoided by taking data directly from the strain gages to an attached data stick, there would be no need for wires leading from the pedal.

#### 7.3 Further Experimentation

This primary purpose of creating an instrumented pedal is for use in further experimentation. This instrumented pedal has proven that it is capable of making comparable measurements to other instrumented pedals produced before it, but this pedal was also made at a lower cost. For cases where an experimenter is concerned with only taking data form a small number of subjects, this may not be an important characteristic, but it could be useful when making measurements from a much larger subject group. If an experimenter wanted to take measurements from hundreds of subjects, it would be beneficial to have several working pedals. We have presented a way to produce 10 or more instrumented pedals for the price of only one of the pedals previously designed by researchers. While these pedals might have a slightly higher level of error, the ability to average so many more subjects could actually reduced total error within an experiment.

Some recommendations should also be made when recreating a pedal. While an aluminum pedal was used for this experiment, it is likely that a steel pedal would produce better results. One reason for this is that steel is slightly less rigid and would most likely give higher levels of strain under given forces. The other reason is that steel is less conductive of heat and therefore would be less likely to be affected by voltage drift and zero offset difficulties. Another recommendation would be to use more than one strain gage in a half Wheatstone bridge circuit or greater. This might produce higher and more consistent levels of strain, especially at low levels of force. We would also suggest

making measurements along the pedal based x axis by putting strain gages along the sides of the central axis of the pedal. While previous experiments such as the Cavanagh and Sanderson data sets have showed that this force is not a major driving force, it is still important because the points of high levels of  $F_x$  can sometimes occur when  $F_z$  is small and therefore  $F_x$  can be the more significant driving force. Another improvement might be made by including insulation around the pedal, especially between the subject's shoe and all electronics, such as the strain gages. We separated the electronics from the rider's shoe by several layers of tape, and a barrier of air, but this was not enough to prevent friction to cause temperature variations and subsequent voltage drift.

# Conclusions

We have outlined the creation a pedal using strain gages that can measure total force applied to a pedal at any given time. The technique for the creation of this pedal has been defined in enough detail to allow for recreation of these results and further use of this design. We included recommendations for improvements that may yield even better results without significantly increasing the cost of the pedal. The instrumented pedal outlined is capable of measuring the strain in the pedal caused by a rider's pedaling force. We have also described the technique for calculating total pedal force from this produced strain. While this design does allow for a level of error above that of previous studies, it was also made for at least 10 times less money than previous pedals. Furthermore, the total weight of the instrumentation (not including a computer) is very minimal. This could allow for the use of this design in overland non-stationary bicycles if a different type of data acquisition module is used. An experiment conducted with three test subjects proved the usefulness of the pedal in a real laboratory situation by producing data that was comparable to previously determined datasets.

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