Thursday 14:00-17:00
Go forth final Paper Assignment

Effects of foot-pedal interface rigidity on high frequency cycling acceleration

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2.671 Measurement and Instrumentation
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Abstract

This paper explores the periodic acceleration due to pedal position in the direction of bicycle travel that occurs at a frequency of about 0.5 hz as a bicycle is ridden. Four different tests are performed to try to isolate the effect of clip-on pedals as compared to regular shoes when riding under various conditions. One rider conducted the tests with an accelerometer and a magnetic sensor attached to the bicycle sensor to measure three axes of acceleration and cadence (Pedaling frequency). The results clearly show a sinusoidal variance with a magnitude varying from 5 m/s^2 to less than 1 m/s^2 of acceleration at a frequency twice that of the cadence - as expected. The effect is most obvious when the bicyclist was sprinting, but is still noticeable to an extent while the bicycle is ridden at a constant speed with regular shoes, but is almost nonexistent at a constant speed with clip in shoes, with the standard deviation for the average of regular shoes 25% greater than with clips.

1. Introduction

Acceleration is very important in bicycle racing and riding because it is integrally related to speed. People pay thousands of dollars to buy wheels that have a slightly lower moment of inertia than a standard wheel in order to expend less energy accelerating. At first glance there is not much acceleration on a bicycle after it gets to a specific speed. However, there are many different modes and time scales at which accelerations occurs as a bicycle is ridden that are not immediately apparent. Low frequency accelerations include the obvious acceleration forwards or backwards as the bicycle speeds up and slows down, as well as the acceleration associated with turning and a lateral acceleration as the bike gets rocked side to side.

Looking at higher frequencies there are many more interesting types of acceleration that are less obvious. There exists a periodic change in acceleration related to cadence which this paper will examine in more detail. However there are also other modes of acceleration with high frequency vibrations such as vibration due to noise and wheel fluctuations to the and the dreaded death shake[1] lateral acceleration that has been known to occurs when bicycles are ridden down-hill at very high speeds.

As has been well studied, the power that a cyclist imparts to the bicycle varies as a function of the pedal angle[2]. While the exact mechanics of the rider-bicycle interaction are complex and vary between cyclists, this variation can be explained by the fact that the largest force that the cyclist is likely to be able to provide is a downward force. While the pedals are at the positions of '3:00' and '9:00' this downward force is perpendicular to the lever arm of the pedal, leading to maximum power. While the pedals are in the upper and lower positions, '12:00' and '6:00' the dominant force direction is parallel to the lever arm, thereby providing a minimum of power. Since the pedals rotate with a roughly constant angular velocity, the result is a sinusoidal transfer of power to the bicycle based on the pedal angle.

Quantifying how this effect changes during different conditions is the purpose of this experiment. The shape of the acceleration versus angle effect is thought to vary significantly based on the style of riding and on the equipment used. It is in the interest of the rider to try to provide as steady of an input of power to the bicycle as possible, since any variation leads to wasted energy. Serious cyclists have adopted shoes that rigidly attach to cyclist's pedals, allowing force to be transmitted to the pedal throughout the pedal stroke. This is thought to provide a more consistent and powerful force than regular shoes and pedals.

This paper studies the effect of these shoes by testing two different types of pedals at two different riding styles for a total of four trials. Regular shoes, which provide a low degree of rigidity between the shoe/pedal interface, as well as clip-in shoes and pedals, which offer a high degree of rigidity, were tested. The two styles tested included sitting down and riding at a constant speed, as well as standing up and accelerating. The acceleration is measured as a function of pedal angle, and then averaged to find statistics showing how each one effects the bicycle's acceleration.

2. Background

2.1 Acceleration and bicycle physics

Although the bicycle is a deceptively simple machine, the actual dynamics are complex. It was not until the early 1900's when people even figured out how exactly the bicycle was stable enough to not fall over.[1] Modern sensing equipment and computers have lead to more study about various aspects of bicycle dynamics that were previously very difficult to measure.

The bicycle experiences a whole range of frictional forces that together act to slow the bicycle down. These forces include rolling friction, wind friction, internal drive train friction, and the conversion of kinetic energy into potential and the reverse (hills). Newton's second law, equation 1, relates these total resistive forces and the acceleration of the bicycle.

$$\sum F_x = m \cdot a_x \qquad \text{Equation 1}$$

On level ground positive acceleration can only be created by the torque transmitted through the pedals. This torque is transmitted through the drive train into the rear wheel, where it is converted into a linear friction force at the point where the tire contacts the ground that pushes the bicycle forward. If the rider is traveling at a constant speed it is known that the sum of resistive forces are equal to the force due to this torque. Therefore, assuming the resistive forces are nearly constant at any given speed, any high frequency change in acceleration is most likely caused by the change in the torque transmitted by the rider.

The integral of acceleration over a period provides a quantitative measure of the amount of change of acceleration, and is also of interest to the dynamics of an accelerating bicycle. This is found by integrating, or summing small samples of the acceleration, shown below as equation 2.

$$\bar{a} = \frac{\sum_{1}^{n_{\max}} \sqrt{\left(x_{acceleration}\right)^2}}{time \cdot Hz_{measure}} \qquad \text{Equation 2}$$

2.2 Accelerometers

Acceleration sensors have become drastically more effective and affordable due to new production processes. They use small masses constrained to move in one dimension that is mounted to a spring. The distance this mass is deflected away from some known point is the actual measurement that is proportional to acceleration as long as the spring constitutive equation is known.

2.3 Bicycle footwear

Cycling has many different types of performance gear including a wide array of different footwear. Almost all serious cyclists use pedals that rigidly attach the wearer's food to the pedal. The cyclist can then use force to push forward and even pull up with one leg while the other leg pushes down. These pedals are confusingly sometimes called 'clip-less' pedals. They are called 'clip-less' even though they attach using a clip-like mechanism because they are not Toe-clips, which is like a regular flat pedal with a strap that goes over the riders shoe. To reduce confusion I will refer to the pedal types from now on as 'clip-in' pedals for the rigidly attached pedals shown in figure 1 and regular shoes or just 'shoes' for the tennis shoes.

The pedals are claimed by many to provide two main benefits, an increase in total power transmitted to the bicycle, and a more constant distribution of this power over one pedal stroke. The pedals also decrease the chance of the rider becoming disconnected from the pedals under fast cadences and high forces, therefore reducing the chance of danger of instability caused when the rider is not fully attached to the bicycle.

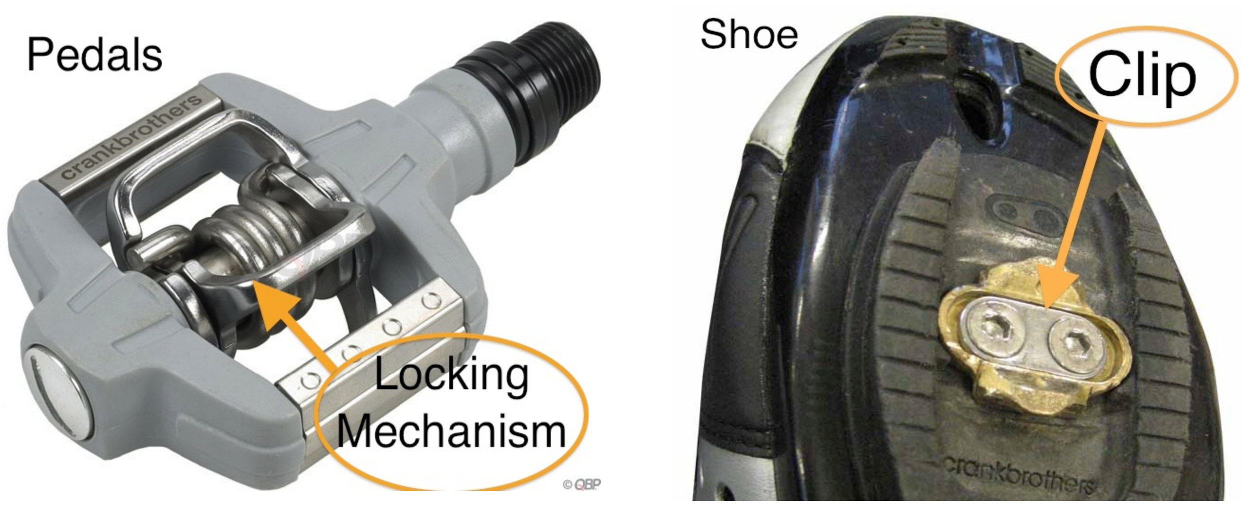

Figure 1: This figure shows the type of pedals and shoes known as "clip-in" the shoes rigidly lock into the pedal to provide much more force transfer. The shoe itself has a very stiff sole to capture all of the energy of the foot without deformation. Although each brand has a different mechanism for accomplishing this task, they all are similar. This style is the Crank Brothers design, which was the type tested in this experiment.

3. Measuring Acceleration and Cadence

The overall aim of this experiment is to quantitatively measure the performance gain, if any, that a cyclist obtains from using clip-in shoes as opposed to regular. To accomplish this each set of shoes/pedal combinations is tested under two different riding conditions. The acceleration and the pedal angle are measured to provide an analysis on the acceleration of the bicycle as a function of pedal angle.

3.1 Preparing the Bicycle

In order to measure the acceleration of the bicycle an accelerometer and a magnetic field sensors was carefully mounted to the frame of the bicycle. The accelerometer was located in a place that had as little noise as possible and provided a relatively flat spot to locate it. Care was taken to ensure that the z axis was pointing straight up, so that gravity did not affect either the x or y accelerations.

The bicycle used was a giant OCR1 61cm frame road bike with 700c diameter tires. The accelerometer used was a Vernier 3axis Accelerometer (3d-BTA) and the magnetic field sensor was a Vernier Magnetic Field Sensor (MG-BTA). The data were collected through a Vernier LAB PRO hooked up to a Macbook pro computer, which was carried in a backpack during the experiments. The sensors were all mounted using zip-ties and double-sided tape, as shown in figure 2.

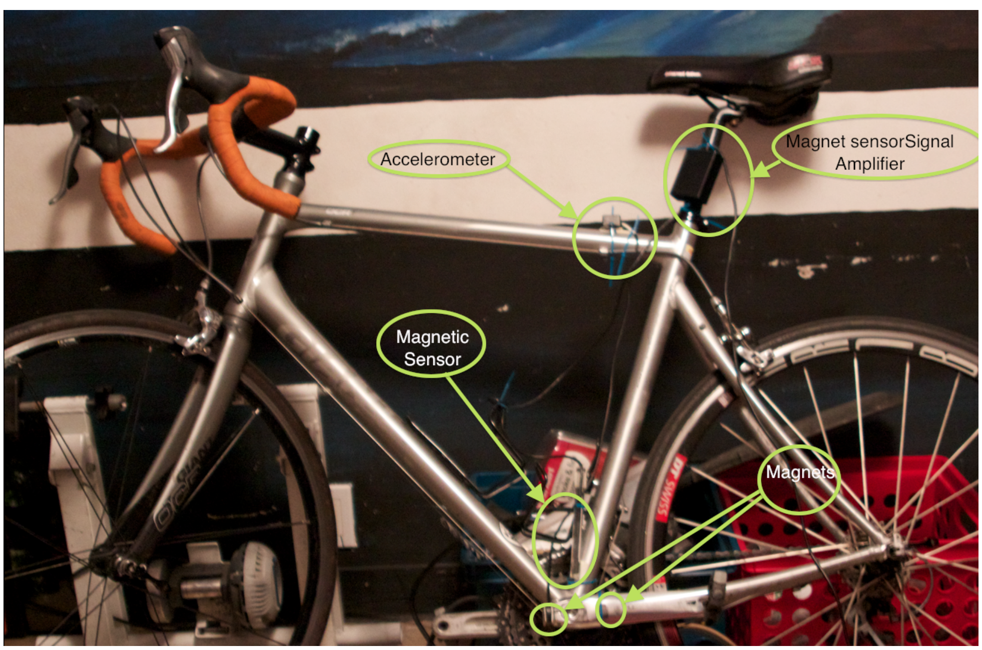

Figure 2: Experiment Equipment. Showing the bicycle and the sensor used in this experiment. The data was collected on a laptop that was closed and placed in a backpack on the test subject.

3.2 Calibrating the sensors.

The magnetic field sensors had two distinct peaks produced by two magnets attached to the pedals and produced smooth data while at first glance the accelerometer data seemed to be random fluctuating to extreme values. The calibration for the magnetic field sensors was accomplished by turning the crank arms to defined positions of 0 degrees (Pedals vertical with left pedal pointing upwards) and 180 degrees. The positions between these 180 and 0 degrees, were not accurate since the rate of change of the magnetic field is not very high in this region as shown in figure 2. However since the motion is very periodic except under extreme conditions, the periods were measured to usually be within ±2 of each other the angle could be approximated to be equal to the linearly scaled span between two successive peaks.

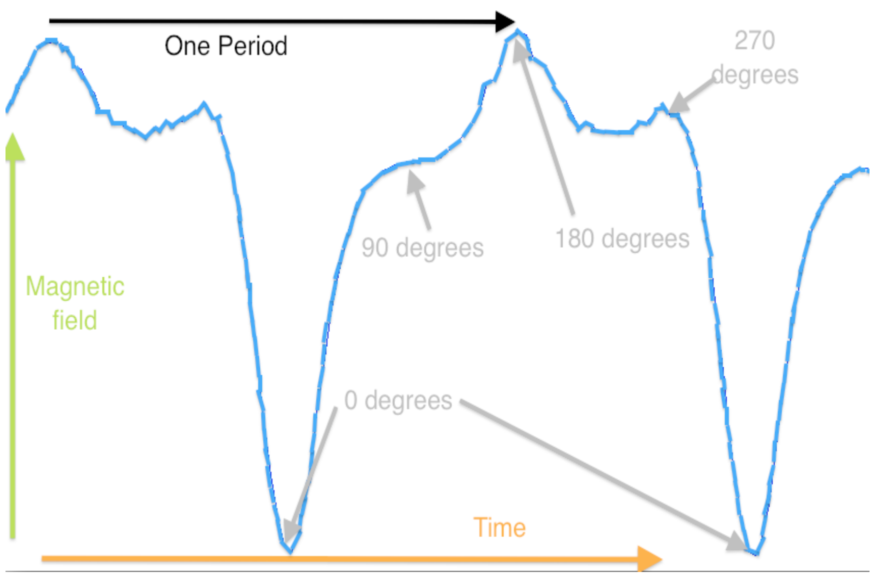

Figure 3: Calibration of Magnetic field sensor. The blue line shows the raw data. The other data is superimposed upon this and shows how the pedal angle was extracted from the magnet data.

Calibrating the accelerometer was difficult because it needed to be level or the acceleration due to gravity would affect the x and y acceleration values. The sensor was calibrated by placing each axis vertically pointed up and then down and setting each value to be plus or minus 9.81 m/s^2. Finding the exact level position where the sensor would show zero acceleration when it was stationary was difficult, and even after careful calibration the values drifted over time and did not appear to be completely reliable.

3.3 Testing Procedures

A sampling time of 60-second with a sampling rate of 100 hz was used to record the information for each test run. All of the trials consisted of the investigator riding the bicycle under different conditions. Most of the tests roughly followed a pattern of accelerating for 50 meters at a sprint, and then pausing for a few seconds, and then maintaining a constant speed for 100 additional meters. For this study two different variables were tested, average acceleration and pedal/foot interface (shoe-type), providing four unique runs.

4. Results and Discussion

The data was analyzed to try to determine the difference that clip-in pedals provide over regular shoes. The different pedal-shoe configurations were tested under two different riding conditions to determine their effect on power and variability as a function of pedal angle.

4.1 Data collection

The data gained in the experiments required some processing before meaningful results could be obtained. As was expected the data from the magnetic field sensor had much less noise than the accelerometers. The accelerations initially varied significantly, and appeared too chaotic to have any trend. This data had many spikes, some in excess of 30 m/s^2. This data was smoothed with multiple 21 unit moving average filters using weighted linear least squares until the data set range did not change significantly. A representative section showing both the raw acceleration data and the smoothed acceleration can be found in figure 4. The large downward spike in the magnetic data (purple line) represents an angle of zero, or the left side pedal pointing up. The second little spike represents 180 degrees, or the left side pedal pointing straight down.

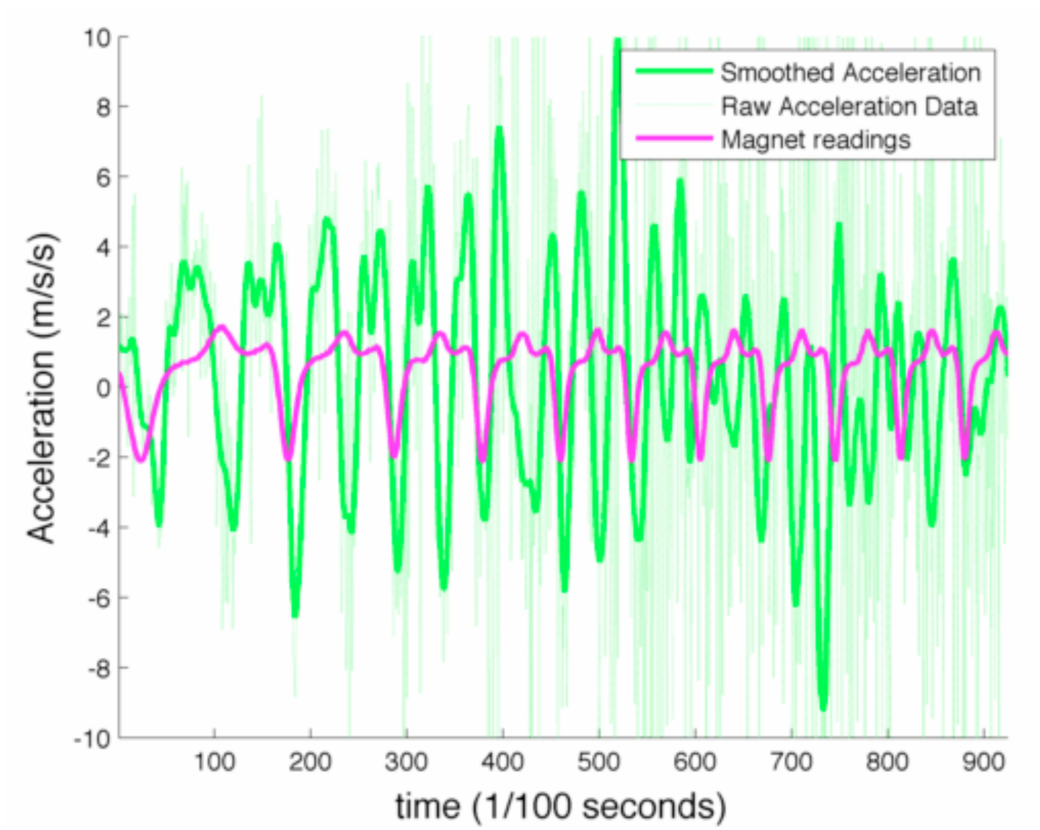

Figure 4: This figure shows both the magnet and the accelerating plotted on one graph. The dark green was smoothed, acceleration, clearly showing the sinusoidal variation of acceleration. This sample was taken while the bicycle was accelerating.

This information very clearly shows that when the pedals are in the vertical position, the acceleration plummets to below zero, while it then increases dramatically while the pedals are near either a position of 90 or 270, or when the angle between the force and the arm is roughly perpendicular. The period for an average acceleration cycle about $0.4 \pm .1$ seconds.

4.2 Results

Four ten second segments of data for each of the four combinations of conditions were then taken out of the raw data and assembled into acceleration versus pedal angle graphs figures 5 and 6. Each graph is the summation of five sequential 360 degree spins (shown in thin green lines). For the constant speed tests the periods were almost identical, and each vector was simply averaged together. However the data for the accelerating case showed a decreasing period as the bicycle came up to speed, and required more complicated math to compute.

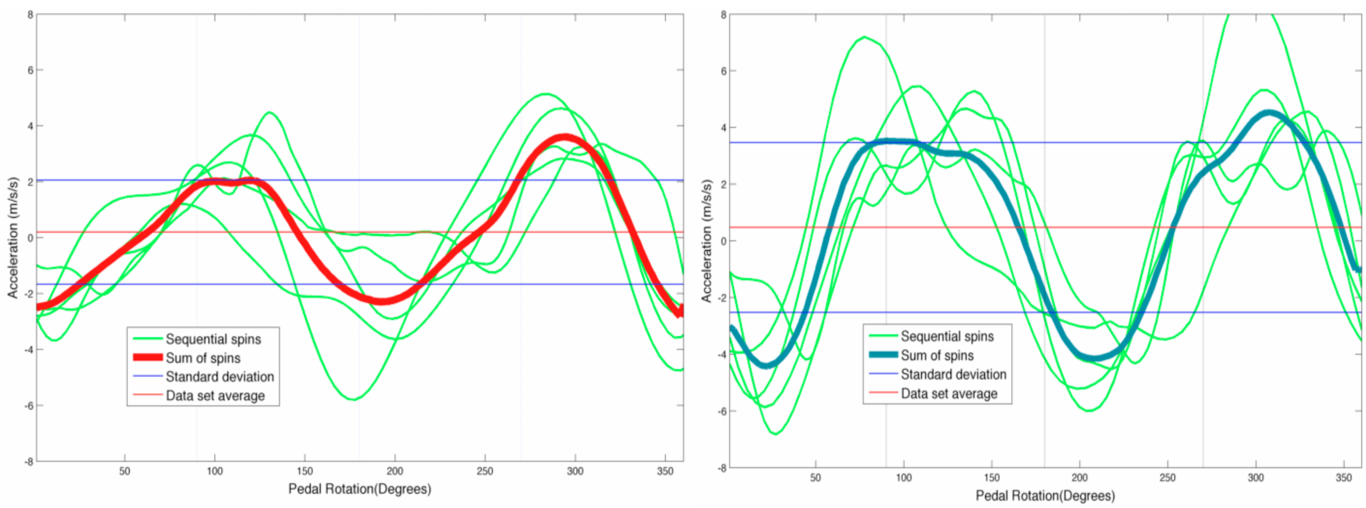

Figure 5: These two graphs show the acceleration versus angle plots for the accelerating cycling with the rider standing up for each pedal configuration. Regular shoes data is shown in red, while clip-in pedals are shown in blue. Both of these clearly show the expected sinusoidal variation in acceleration.

The sinusoidal effect of the acceleration is likely magnified by nature of the riding style used. Since the rider was standing up and exerting maximum force into the bicycle, the strongest muscles and the full force of the rider's weight is felt by the pedals. While the data for the clip pedals shows a higher standard deviation than the shoes it is not scaled for total acceleration. The total acceleration imparted to the bicycle with the clip in pedals is higher than with regular shoes.

While the bicycle was ridden at a roughly constant speed the sinusoidal variation is less dramatic. While the variation can be found somewhat in the regular shoe data, it is almost non-existent in the clip-in data.

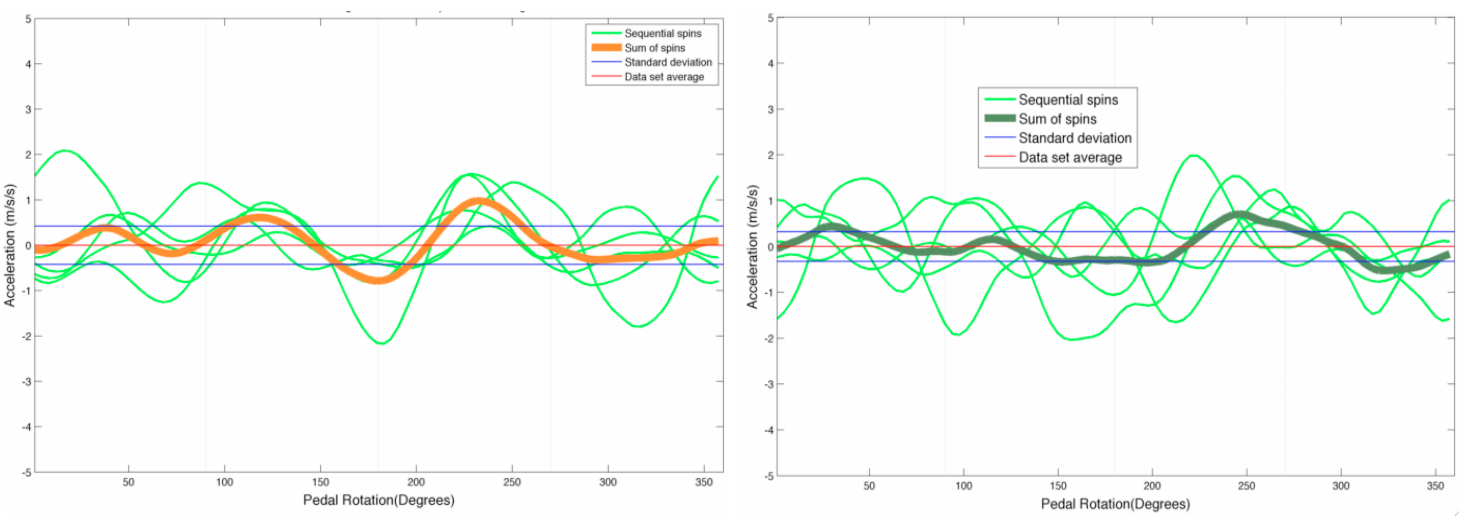

Figure 6: These two graphs show the acceleration versus angle plots for the constant speed seated style of bicycle riding or each pedal configuration. Regular shoe data is shown in orange, while clip-in data is shown in dark green. Both of these show a relatively small amount of sinusoidal variation as a function of angle compared to the graphs in figure 5.

The data was in figure 5 was scaled according the average acceleration of each sample. This was then assembled into figure 7, showing the average accelerations and the associated standard deviations for each of the four configurations tested.

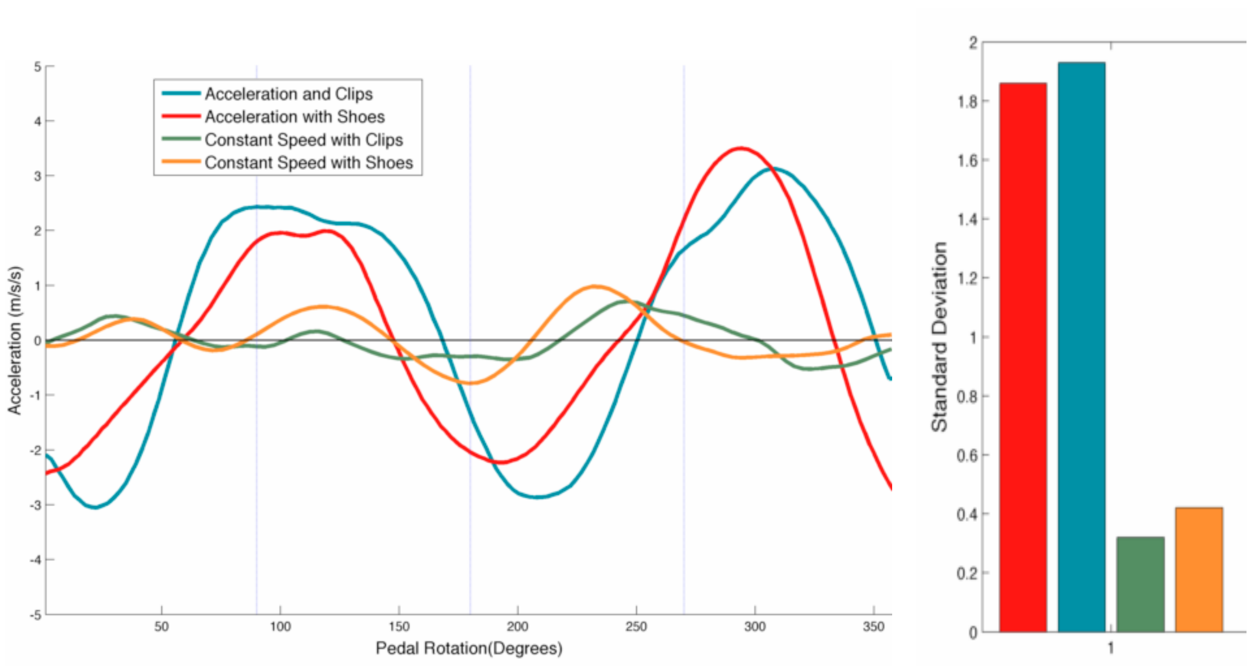

Figure 7: Results Summary. The colors match the graphs from figures 5 and 6 and shown how the accelerations vary with pedal stroke for each of the four trials.

Additionally the integral of acceleration for each was calculated according to equation 2. This provides a measurement of the total change in speed of the bicycle over a pedal stroke. This in turn can be equated roughly to the energy lost due to unnecessary accelerating.

Table 1: Shows some calculated parameters for the four different runs.

Data run	Standard Deviation	Integral of acceleration (Eq 3)	Average acceleration	Scaled Standard Deviation
V ~ constant, Shoes	**0.42**	**1.64**	**0**	**n/a**
V ~ constant, Clips	**0.32**	**1.32**	**0**	**n/a**
A > 0, Shoes	**1.86**	**14.86**	**.15**	**2.7**
A > 0, Clips	**2.99**	**21.8**	**.20**	**2.9**

Discussion:

All of this data should be considered with the knowledge that only one rider was tested, and even across one rider, the technique is not perfectly consistent across different runs of collected data. A change in style of riding would be enough to cause the results to change significantly. Therefore these exact numerical results should not be made to be too significant, however the trends demonstrated with this data are likely to provide some insight into the different configurations of pedals.

The information in table 1 provides us with enough information to evaluate the different types of pedals. It is clear from the data that the clip-in pedals are superior to the regular shoes in total power delivered to the bicycle. They provided an 34% increase in average acceleration as opposed to the regular pedals and shoes. This is most likely due to the advantage that the rider can pull up to apply force to the bicycle.

The effect of the pedal configurations on the consistency of the power over one pedal stroke is more difficult to discern. However the important data that should be taken into consideration is the standard deviation of the different configurations tested under an approximately constant velocity. This shows a 25% decrease in the standard deviation. The data from the accelerating style of riding is less conclusive in this regard, because the style of riding inherently should cause significant variation. While at first the standard deviation for the clip-in configuration is higher, once it is scaled for the average acceleration the two values are similar.

It is also interesting to note that integral of accelerations of the standing up style of riding are over ten times that as the sitting style. Although it is general knowledge that this type of riding is less efficient, this shows the effect to be significant. Assuming that energy is lost in proportion to this value, this hints at how much less efficient this type of riding might be.

5. Conclusions

Although the fact that the more rigid and the fewer degrees of freedom the foot-pedal interface has the acceleration is more even for a given value was predicted, the results are a little more complex. This hypothesis that the acceleration will be smoother for the clip in pedals is true to some extent but is not entirely proven. While the standard deviation for the non-accelerating segments shows an approximately 25% less variability, the accelerating data is inconclusive. Also the standing-up and accelerating style of riding causes much more variation in acceleration as compared to the sitting style. So to cycle the most efficiently this paper suggests that the rider remain seated on the bicycle and use clip in pedals.

Further interesting research could look at the same profiles but for climbing a steep hill, perhaps at different gear ratios, and could include different brands of pedals and toe clips. An analysis of the other axes of acceleration could also provide some interesting insights into what is occurring in the lateral and vertical directions, and might be able to be used to quantify the bumpy-ness of the road or other interesting information.

Acknowledgments

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References

[1] David J. N. Limebeer and Amrit Sharma, *Burst Oscillations in the Accelerating Bicycle* Appl. Mech. 77, 061012 (2010), DOI:10.1115/1.4000909

[2] William Bertucci, Frederic Grappe, Amaury Girard, Andrew Betik, Jean Denis Rouillon, *Effects on the crank torque profile when changing pedalling cadence in level ground and uphill road cycling*, Journal of Biomechanics, Volume 38, Issue 5, May 2005, Pages 1003-1010, ISSN 0021-9290, DOI: 10.1016/j.jbiomech.2004.05.037.)