DESIGNING A SENSOR; A FORCE PEDAL FOR THE BICYCLE

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INTRODUCTION

The results presented in this paper are in response to our need for a device to measure forces in the knee while riding a stationary bike. Current pedal designs used to measure such forces do so indirectly and employ either piezoelectricsensors or strain gauges. Hull and Davis (1981) designed an instrumentation system that measured 6-axis pedal loading. Thirty-two strain gauges were mounted within a modified pedal body. The gauges were connected into eight, fully temperature-compensated Wheatstone bridge circuits at four locations. A compressive force reacts on the first four gauge locations while the last four exhibit zero strain. The shear force produces strain at the last four gauges with zero strain on the first four. Subsequently, there is little cross-effect between the two component measures at each ring. When example data were taken (clip pedal with bike on rollers), the shear and compressive forces were similar to previously reported results.

In 1985, Gregor, Cavanagh, and LaFortune designed left and right side pedals using strain gauges to build a force cube to measure normal and tangential forces on the pedals. The normal, or perpendicular, force was measured by four foil strain gauges adhered to the cube. Two gauges were on top of the cube and two were on the bottom. All four gauges were connected to a Wheatstone bridge amplifier. The tangential or shear force was measured by two pair of gauges bonded to two beams that were parallel to the upright edges where the foot sat. The tangential gauges were also connected to a bridge system. The pedals were attached to a conventional racing bike mounted on a stationary system that simulates road riding.

Broker and Gregor (1990) describe a dual piezoelectric transducer setup. The transducers were mounted between the pedal body and shoe/pedal interface. The dual setup allows for "measurement of three components of a uniaxial load, moments about the pedal's vertical axis (Mz), and the location of the applied load (p.395)." Accuracy of measurement for loads and moment was +5%. The uniaxial outputs were summed to represent total component load. The individual outputs were also used to calculate Mz and the point of force application.

Most of the pedal designs are used for road or racing bikes. The pedal used by Ericson and colleagues in two studies (1984,1986) for the stationary bike was similar to the design by Broker and Gregor (1990) except that only one piezoelectric transducer was used. It was placed in the left pedal and only allowed for force measurements in the three orthogonal planes.

Cost and limited resources are frequently the prohibitive factors in most clinical settings involving data acquisition. The cost of these pedals can reach $18,000 (Roger Brath, Kistler Corporation, personal correspondence, March, 1994). Thus, our experiment involved designing and constructing a relatively simple, inexpensive force pedal.

METHOD AND PROCEDURE

Using existing technology is fine if one understands its limitations and it fits in the budget. Further, the device must measure the desired parameters. Since it has been indicated that our primary goal is to measure forces at the knee, we are faced with the question; how can this be done? Thus, what measurement must be made? One approach might be a device that could measure the pressures directly, but this would involve invasive implants. Hence, we are faced with using a model that computes the forces at the joints given the forces between the foot and the pedal.

The purpose of the sensor is to provide a method for acquiring a voltage signal that is proportional to the forces at the pedal for an experiment.that involved 17 subjects exercising on a stationary bike Approximately half of the subjects were recovering from knee surgery. All were required to exercise in a loaded environment.

In addition, a PEAK (Englewood, CO.) system was used to acquire kinematic information which related to the total activity of the individual. The PEAK system was also used as the ADC for the sensor system.

DESIGNING A SENSOR

As previously mentioned, some of the sensor systems already available are quite expensive. Others require extensive reconfiguration for use in the experiment to be performed. Thus we elected to design and construct our sensor system from the ground up. This required that we configure a device that would react to the selected forces.

In discussing the primary experiment, which could be performed in 2-D or 3-D, it was realized that our engineering resources were limited with regard to what we could construct. Thus we elected the 2-D model which required that our sensor system measure forces normal to the pedal and tangential to the pedal. Any mechanical configuration must be able to decouple the two forces. It was quickly realized that the problem of decoupling the two forces was central to the design. Next, was the problem of designing the actual sensing system. Two sensors were available: the strain gauge and the piezoelectric. At the time of construction, the only piezoelectric sensor available exceeded our budgetary limitations. Thus we used strain gauges. We select 350 ohms gauges with dimension 2.5x1.8mm. Further, familiarity in the use of strain gauges was a factor used in our selection process. Each sensor subsystem consisted of four strain gauges configured as a bridge. In the subsystem used to measure the normal forces, only one gauge would be deformed by the load. In the system used to measure the tangential forces, all four gauges were designed to react to the forces; two were used to measure the forces directed anteriorly and two were used to measure those forces directed posteriorly.

A regular pedal for stationary bicycles was used as the foundation for the force pedal. Two plates of aluminum were cut to fit on the top and bottom of the rubber pedal. A 90-degree angled piece of aluminum was cut into 2 pieces to fit across the width of the pedal anteriorly and posteriorly.

The two angled aluminum elements were used to measure the shear. Two strain gauges were placed on each of the upright portion of the angled aluminum supports. The orientation of the gauges was perpendicular to the pedal surface. All contacts and soldered wires were checked with a volt meter for conductivity and cross talk.

The normal subsystem consisted of: three of the gauges attached to the bottom of the aluminum plate with the fourth gauge mounted on a flexible mounting bridge. This bridge was located on the top plate.

A 9-volt battery was used as a power source for each bridge. Two 4-pin jacks were installed on the communication lines about 20cm from the pedal. The output signal was amplified using a Biocommunications Electronics (Model 215, Madison, WI) amplifier. Both channels were set to low pass filter of 50 Hz. The shear channel had a gain of 1000 and the compression channel was set to a gain of 500.

CALIBRATION OF THE PEDAL

Once the pedal was constructed and raw signal received from each component, the pedal underwent initial calibration to pounds (lbs) of force. In the computer program that converted the raw units of force to the calibrated units, the additional conversion to Newtons (N) of force was made. The two force components were calibrated with the pedal aligned horizontally and fixed.

The normal component was calibrated by applying known weights vertically on the top of the pedal in such a way that only the normal subsystem would react. In calibrating the normal subsystem a baseline voltage was first acquired by measuring the voltage in a zero force situation. Using five different weights we recorded the voltage with the purpose of defining a relation between voltage and force. This calibration scheme was employed over several different days, testing for consistency. We used Cricket Graph (Ver. 1.2, Malvern, PA) to plot the voltage verses the weight. Using Cricket graph's equation feature, an exponential equation was fitted to the data. Variation between the data curve and the equation curve began to show at just above 250 volts. However, pilot studies yielded maximum raw normal voltages of no greater than 240 volts. Thus mathematical equation provided an excellent conversion tool.

The shear components were calibrated by applying known forces via a spring gauge against the angled aluminum directed along the horizontal. The spring gauge was secured to a piece of flexible rubber attached to a wooden block. A baseline voltage reading was taken. The rubber and block was clamped to the top of the pedal. Another voltage reading was taken. Six different amounts of force were applied in both the anterior and posterior directions by pulling on the spring gauge. The voltages recorded were adjusted mathematically by adding or subtracting the difference of the baseline and clamped voltages. If the voltage obtained during the clamped trial was smaller than the baseline voltage, the difference was added to the voltages recorded with force applied. If the clamped trial voltage was greater than the baseline reading, then the difference was subtracted from the voltages recorded with force applied. This was done to negate the effect of the voltage produced by clamping the block to the pedal.

The adjusted voltages were plotted against the weight with Cricket Graph. As with the normal force, the equation feature of the software was used to establish linear equations for posteriorly-directed and anteriorly-directed force.

Although the equations were similar in slope, the equations differed from collection to collection. Therefore, shear calibration was performed at the beginning of each data collection session. The equations developed were used only for that day's session.

RESULTS AND DISCUSSION

The overall cost of the pedal was approximately $300.00. Therefore, one of the goals of the study was met. We were able to construct a relatively inexpensive pedal. The accuracy of the pedal as well as problems encountered are presented below.

Decoupling of the shear and normal forces could not be completely achieved. The design and bridge construction of the pedal allowed for separation of the normal force calibration without gathering information from the shear gauges. However, shear calibration could not be performed without engaging the normal gauges. During data collection, the foot was in contact with both the shear and normal sensors. One sensor subsystem could not be activated independently of the other. We should note that due to a normal reacting force from the shear subsystem the normal force was generally underestimated.

As data collection progressed, it became more difficult to decrease noise introduced into the system at the connections. Wires broke requiring repair. The cable-to-cable connectors were subjected to floor contact as the crank ann proceeded past bottom dead center. This physical contact was found to be a major source of noise in the form of large spikes in voltage during the crank cycle. The wear and tear effect on the system was the reason for cessation of data collection resulting in reducing our sample size to n= 14. However, the pedal was in use for about 2 years for testing and pilot studies. Although problems became progressively worse, the overall durability of the pedal was fair.

The data collected from the pedal were calibrated and combined with

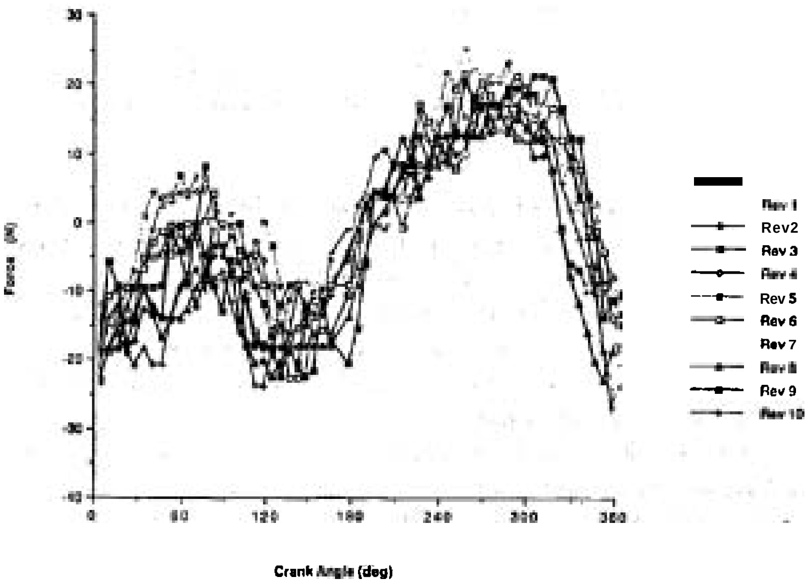

Figure 1. Pedal shear force for 10 revolutions for injured subject 1 at 1 kg.

the kinematic data to calculate knee normal forces, knee tangential forces, and sagittal plane knee moments of the subjects riding. The data was defined by sampling the output signal for 9 full revolutions. We selected multiple revolutions to test for consistency of the output signal. Sampling rate was 60 samples/second. Figures 1 and 2 present examples of pedal shear and normal forces obtained. The average deviation from the mean is about 4.0%.

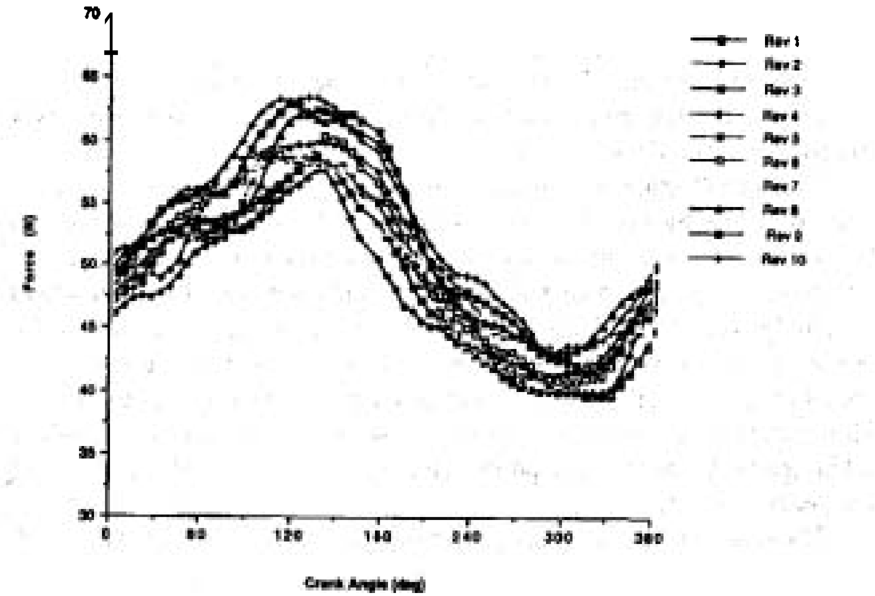

Figure 2. Pedal normal force for 10 revolutions for injured subject I at 1 kg.

CONCLUSION

An inexpensive, yet reliable pedal was able to be constructed. There were problems with decoupling, quantification of the normal force, and noise. The pedal was fairly durable. Information obtained using this pedal was used to investigate the forces induced in the leg of a subject during a single revolution of the pedal. We used the system to compare such forces encountered by subjects having knee dysfunctions against healthy subjects.

In addition, we have redesigned the pedal to better quantify the normal force as well as reduce coupling between the normal and the tangential forces. Also, we are currently considering a model which would allow us to use the velocity of the wheel with the known forces and the PEAK image to ascertain the same information without altering the cycle's original pedal.

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