

Development of a System for Measuring the Three-Axis Pedal Force in Cycling and Its Applications

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Abstract—For cycling, the analysis of the pedal force is one of the important factors in the study of exercise ability assessment and overuse injuries. In past studies, a two-axis measurement sensor was used at the sagittal plane to measure the force only in the anterior, posterior, and vertical directions and to analyze the loss of force and the injury on the frontal plane due to the forces in the right and left directions. In this study, which is a basic study on diverse analyses of the pedal force that consider the forces on the sagittal plane and the frontal plane, a three-axis pedal force measurement sensor was developed to measure the anterior-posterior (Fx), medio-lateral (Fz), and vertical (Fy) forces. The sensor was fabricated with a size and shape similar to those of the general flat pedal, and had a 550g weight that allowed smooth pedaling. Its measurement range was ± 1000 N for Fx and Fz and ± 2000 N for Fy, and its non-linearity, hysteresis, and repeatability were approximately 0.5%. The data were sampled at 1000 Hz using a signal collector. To use the developed sensor, the pedaling efficiency (index of efficiency, IE) and the range of left and right (medio-lateral, ML) forces were measured with two seat heights (low and high). The results of the measurement showed that the IE was higher and the force range in the ML direction was lower with the high position than with the low position. The developed measurement sensor and its application results will be useful in understanding and explaining the complicated pedaling technique, and will enable diverse kinematic analyses of the pedal force on the sagittal plane and the frontal plane.

Keywords—Cycling, Index of effectiveness, Pedal force.

I. INTRODUCTION

THE pedal force is important in the study of exercise ability and overuse injuries during cycling. A cycle has a driving force when the vertical force from the leg is finally delivered as the pedal driving force. Diverse commercial systems have been developed to measure the pedal force produced by such driving forces. Representative examples include the SRM powermeter (SRM, Jülich, Germany) and the PowerTap system (CycleOps, Madison, USA). Force measurement methods with torque sensors are used to determine the pedal power and assess the exercise ability. However, the existing equipment cannot measure the actual pedal force, and has a limitation in its application to diverse studies on efficient force transmission analysis and injury. In the preceding study, transducers such as strain gauges or piezo-resistive sensors (load cells) were used to develop diverse meters for measuring the force applied to the pedal [4], [12]. Thus, the pedal force effectiveness was

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analyzed according to the exercise posture, and the joint load was analyzed through modeling [11]. The pedal force efficiency (the ratio of the force perpendicular to the crank to the total force applied to the pedal) is used as the index of effectiveness (IE) [5] and for the analysis of the pedaling technique on the sagittal plane [2], [8], [14]. However, a recent study reported that an index of IE alone was insufficient to explain the complicated pedaling technique [10].

In addition, many past studies used two-axis load cells to measure the pedal forces in the normal (vertical) and anterior-posterior (AP) directions on the sagittal plane, but were unable to adequately analyze the loss of force and the injury due to the medio-lateral (ML) force on the sagittal plane.

In this study, a three-axis pedal force measurement system was developed to enable diverse analyses that consider the forces on both the sagittal and frontal planes. The system had a three-axis load cell to measure the pedal force, and its weight and size were minimized to obtain a shape similar to that of the existing commercial pedal. The developed system was used to examine the change in the pedal force on the sagittal and frontal planes according to the pedaling posture with different seat heights.

II. METHOD

A. 3-Axis Pedal Force Measuring System

The three-axis pedal force measurement system has a three-axis pedal force measurement sensor, a signal amplifier, and a self-developed measurement program. During pedaling, the force applied to sensor is outputted in the form of a voltage change, and a signal amplifier is used to amplify the output signals. The amplified signals are collected using a self-developed program.

1) 3-Axis Force Measuring Sensor

Fig. 1 shows the three-axis pedal force measurement sensor attached to the crank. The sensor was fabricated in the same form as that of the general flat pedal.

Fig. 2 shows its size and appearance. Its case was made of aluminum by a load cell production manufacturer to ensure light weight.

Fig. 3 shows the inside of the sensor and the dotted rectangles show the area where the device is connected to the upper plate.



Fig. 1 Three-axis Pedal Force Measurement Sensor installed Device

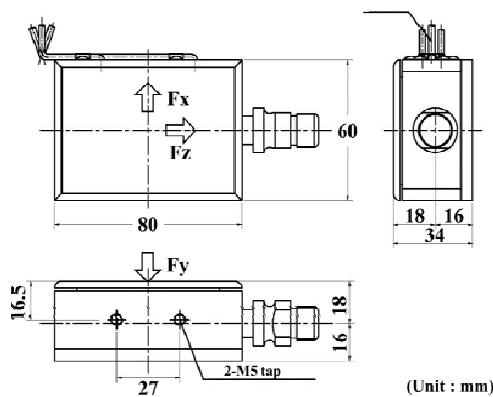


Fig. 2 Three-axis Pedal Force Measurement Sensor Appearance

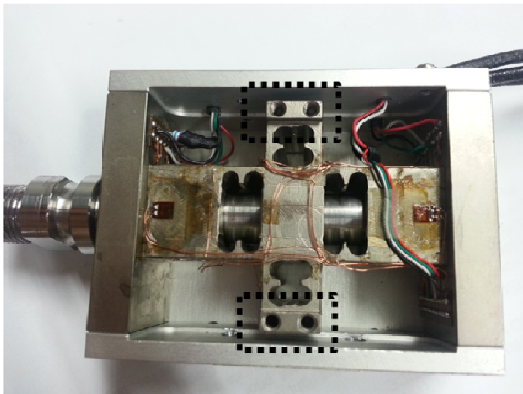


Fig. 3 Three-axis Pedal Force measurement sensor inside

During pedaling, the force applied to the upper plate is transmitted to the dotted rectangle areas to change the strain gauge, and is outputted as a voltage through the internal Wheatstone bridge. The shaft of the sensor, which is connected to the crank arm of the bicycle, cannot allow normal pedaling unless it is centered at the pedal. Therefore, the shaft was positioned at the center of the strain gauge to allow normal

pedaling, and bearings were inserted at both sides to enable smooth pedal rotation and distribution of the load applied to the pedal.

For the three-axis pedal force measurement sensor, the force in the AP direction was set as F_x ; in the ML direction, as F_z ; and in the vertical direction, as F_y . The force in the F_x and F_z directions was about as large as the small forces for pedaling such as the push and pull on the pedal, and its range was set at ± 1000 N. However, the force in the vertical direction F_y was large, and its range was set at ± 2000 N. DC 10 V was applied to the strain gauge in the sensor.

2) Signal Amplifier

The output voltage of the sensor was 6-10 mV when a 10V voltage was applied. Because the output signal was very small, it was significantly affected by the noise. Therefore, the noise was removed, and a signal amplifier was used to amplify the signals. The signal amplifier was the DN-AM100 model (Dacell Co., Ltd., Korea), which had a step-by-step filtering function and an automatic temperature compensation circuit.

3) Three-Axis Pedal Force Measurement Program

The three-axis pedal force measurement program used data acquisition (DAQ) to read into the computer the signals amplified by the signal amplifier. The DAQ software and the three-axis pedal force measurement program used were NI USB-6215 and Labview2010 (National Instrument Corp., USA), respectively. The signals collected from the DAQ software were converted to the force applied to the pedal using the manufacturer-provided calibration data. The sampling frequency for the pedal force data was set at 1000 Hz to make the data storable in text files. The text files were saved in the order of Time, F_x , F_y , and F_z (Fig. 4).

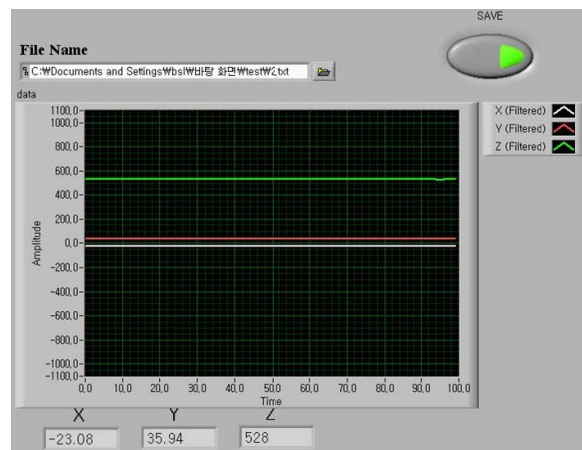


Fig. 4 Front panel of the measurement program

B. Example of the Application of the Three-axis Pedal Force Measurement System

1) Subject

The subjects in this study were two normal persons who had no abnormality in their musculoskeletal system and could perform normal pedaling. They were provided the full

description of the test method, and they signified in writing their agreement to participate in the test before the conduct of the test.

2) Test Procedure

In this study, the developed system was used to examine the pedal force change on the sagittal and frontal planes according to the pedaling posture. To simulate the change in the pedaling posture, the Homes method [3] was used to set high and low seat heights that corresponded to the knee flexion (25° and 35°). The three-axis pedaling force during the pedaling with different seat heights was measured under a 150W load and a 60rpm pedaling condition for 3 minutes.

3) Test Equipment

A fixed bicycle, the developed three-axis pedal force measurement system, a 3D motion analyzer, and a fixed bicycle with an adjustable frame size were used for the test, and the I Magic trainers program (Tacx, Wassenaar, the Netherlands) was used for load control and cadence measurement. In addition, the three-axis pedal force measurement sensor developed in this study was attached. The position and angle of the sensor were acquired through the 3D motion analysis system (Motion Analysis Corp., USA), which consisted of six infrared devices. 9mm reflective markers were attached to the crank shaft and pedal to calculate the crank and the pedal angle. The three-axis pedal force measurement system and the 3D motion analysis system acquired data by synchronizing the starting point.

4) Data Analysis

Out of the data measured for 3 minutes, only the data for 2 minutes were used. To remove the noise, a second-order zero-delay Butterworth filter with a 6Hz cutoff frequency was applied to the data for the 3D motion analysis system. The fourth-order Butterworth filter with a 4Hz cutoff frequency was applied to the data of the three-axis pedal force measurement system. The pedal force data of the system were calculated as the average of each interval (the top dead point to the top dead point). With such data, the pedal force efficiency (IE) on the sagittal plane and the force in the ML direction on the frontal plane were calculated. The IE was calculated using the resultant force (RF) on the sagittal plane produced by the anterior-posterior force and the vertical force, and the effective force (EF) that was vertically applied to the crankshaft. Equation (1) shows the IE calculated from the ratio of the EF to the RF. The range of force in the ML direction was set as the difference between the maximum and minimum for each interval, and the force was calculated as the average in the range of each interval.

$$IE = \frac{\int_0^{360} EF dt}{\int_0^{360} RF dt} \quad (1)$$

III. RESULT

A. Development of the Three-Axis Pedal Force Measurement Program

In this study, the three-axis pedal force measurement system, which measured the force applied to the pedal during pedaling, was developed. The three-axis pedal force measurement sensor weighed approximately 550 g and had almost the same size as that of a normal flat pedal (80×60×34 mm). The force was measurable within the range of ±1000 N for the Fx and Fz axes, and within the range of ±2000 N for the Fy axis. The non-linearity, hysteresis, and repeatability were approximately 0.5% of the output (Table I).

TABLE I
SYSTEM SPECIFICATION

Specifications	Accuracy
Rated capacity(R.C)	Fx, Fz 1000N Fy 2000N
Rated output(R.O)	0.6~1mV/V
Non linearity	0.5% of R.O
Hysteresis	0.5% of R.O
Repeatability	0.5% of R.O
Degree of interference	±4%
Insulation resistance	2000MΩ
Temperature range, Compensated	-10°C ~ 40°C
Temperature range, Safe	-20°C ~ 70°C
Excitation recommended	10V DC
Safe overload	120%

B. Application Results of the Three-Axis Pedal Force Measurement System

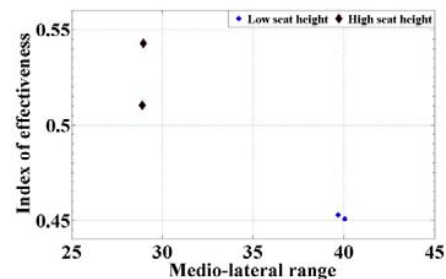


Fig. 5 Range in the IE and ML directions according to the seat height

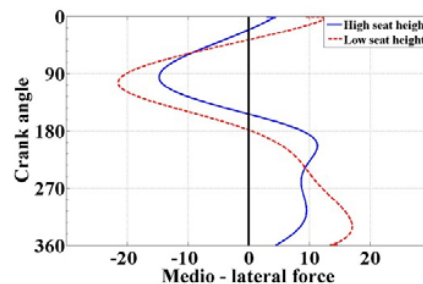


Fig. 6 force in the ML direction according to the crank angle

In this study, a three-axis pedal force measurement system was developed and used to examine the range of force in the IE

and ML directions according to the seat height. Fig. 5 and Table II show the test results with two subjects and two seat heights. Fig. 6 shows the graph for the ML direction. The low seat height led to a low IE and a high ML range, which are shown in Fig. 6. In addition, the force range in the ML direction decreased with a high seat height (Fig. 6).

TABLE II
ML RANGE AND AVERAGE IE FOR EACH INTERVAL ACCORDING TO THE TWO SEAT HEIGHTS

Seat height	Low		High	
	ML range	IE	ML range	IE
Subject 1	40.05	0.45	28.88	0.51
Subject 2	39.68	0.45	28.95	0.54

IV. DISCUSSION & CONCLUSION

During pedaling, the leg motion on the sagittal plane becomes the rotating motion according to the geometrical structure of the cycle. By measurement the force applied to the pedal, the detailed magnitude and direction of the force can be determined, and modeling analysis is made possible through kinematic analysis [13] and simulation. In the preceding study, pressure and strain gauges and piezo-electric sensors were used to measure the pedal force [11]. Thus, studies have been conducted on pedal force measurement, exercise ability, and leg joint injury [1], [2], [9]. However, most of the preceding studies were limited to the pedal force on the sagittal plane. The driving force of the cycle is mostly produced by the rotating motion in the AP and vertical directions of the pedal on the sagittal plane, but the loss of force and the joint injury due to the rotating moment must be considered [6], [7].

In this study, a pedal force measurement system was developed using a three-axis load cell to measure the pedal force applied to the frontal plane and to the sagittal plane. The system allowed the analysis of the loss of force and the joint injury due to the rotating moment. The weight and size of the pedal force measurement sensor were minimized so that its shape would be similar to that of the existing pedal, and the hysteresis, non-linearity, and repeatability were good at approximately 0.5%. The developed system was used to examine the possibility of diverse analyses according to the pedal force on the sagittal and frontal planes with different seat heights. The high seat height (knee angle: 25) resulted in a higher IE and a smaller ML range than with the low seat height (knee angle: 35). Apart from the higher pedal force and energy efficiency with a higher seat height suggested by preceding studies [15], [16], more multilateral analyses will be possible using the loss of force on the frontal plane. It is expected that the developed system can be used for diverse kinematic analyses with the pedal force on the sagittal and frontal planes, and will be a useful measurement device for understanding and explaining the complicated pedaling technique.

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