Design of Pressure Measurement Instrument for Smart Footwear

Kadek H. Sanjaya, Latif Rozaqi, Gien Y. W. Simanungkalit, Aditya N. Iksan, and Muhammad Y. Yuriis

Abstract— **Walking, which is a type of gait, is a very common yet energetically demanding activity in daily life. In this study, we develop smart footwear to measure and record walking patterns which in the future may indicate the user's health condition. The walking patterns are recorded by using several Force Sensing Resistor (FSR) sensors on the footwear. In this manuscript, we discuss the research to make a compressive force mechanism from the FSR pressure sensor to the computer as a stage for the development of the smart footwear. The compressive force is necessary to enable us to analyze the walking patterns. The study was performed in four stages. The first was manual measurement using a force gauge to apply force on the FSR pressure sensors. The second stage was making a simple Arduino circuit and program to detect the measurement. The third was making a voltage divider circuit to recognize the voltage on the sensor, accompanied by making a voltage detection program from the sensor. And the last stage was performing the main experiment followed by data analysis and report. The cftool MATLAB software was used to do curve-fitting and the Arduino software was needed for writing and uploading programs or code to the Arduino board and doing force measurements. The results show that the average minimum error is 3.4% and the maximum error is 25.9%. We also found that the largest error occurs at a force of 50 N, while the distribution of the smallest error occurs at 20 N. It seems that FSR pressure sensors have poor resistance to be applied to smart footwear. The problem may be solved by using better FSR sensors or simplifying the measurement, as well as by using a more sophisticated estimation such as Kalman filter.**

Index Terms— **Gait analysis, FSR pressure sensor, voltage divider, error test**

I. Introduction

ONE specific trait of legged animals is gait which is defined as certain patterns of leg movement for moving from one place to another [1]. The movement is called locomotion. In the study of gait, researchers have been studying the different types of locomotion for many years in order to be able to describe the characteristics of each gait type. The types of locomotion which are achieved by various gait patterns are associated with the anatomic features of the legged animals [2]. The most numerous gait types among legged animals are observed on quadrupedal animals. The gait types of quadrupedal animals include walk, amble, trot, pace, canter, and gallop. In bipedal humans, the types of gait are fewer which include out of phase bipedal movement (walking and running) and in phase bipedal movement (jumping).

Despite walking is a common activity, the fundamental understanding of walking is still evolving to follow the development of science and technology [3]. In this study, we develop smart footwear to record the gait patterns connected with a smartphone. This footwear will be able to analyze the walking patterns of its users in real-time. Pressure sensors are placed in the footwear to record variables such as gait speed, step length and width, ankle joint motion, pressure on the foot sole, and symmetry between these variables between the left foot and the right foot. After the analysis of digital signals, information can be displayed on the user's smartphone to assess his condition based on his gait patterns. The benefits of smart footwear will be very broad, starting from a basic understanding of walking to the assessment of health and physical condition by comparing normal people's walking patterns with people who have abnormalities due to age, illness or injury [4]. Such a tool will facilitate an early and accurate prognosis in the event of an abnormality, as well as provide objective information about the success of treatment interventions and walking therapy to patients [5]. As the healthcare system in a developing country like Indonesia has been characterized by a lack of efficiency and effectiveness that in the end burdens the patients [6], the development of smart footwear is expected to mitigate these problems.

In the early stage of the smart footwear design, we developed a testing prototype using a pair of sandals as the platform. Five FSR model 400 pressure sensors (Interlink Electronics Inc., USA) were attached to each sandal. The FSR pressure sensors were able to provide continuous force resolution with the device rise time less than 3 microseconds. They were positioned as such so that they lie underneath the following landmarks of the foot sole: big toe, 1st, 3rd, and 5th metatarsals, and calcaneus, as illustrated in Figure 1 and has

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been described in previous publications [7][8]. The pressure sensors then connected to an Arduino Nano Atmega 168 microcontroller with a baud rate of 19200 bps, which allowed a sampling rate of 1000 Hz. The microcontroller is further connected to either a smartphone or a personal computer. The prototype generated electrical signals in the form of electrical potential (in Volt), but not in Force Unit (in Newton). As such, in this manuscript, we discuss the research to make a compressive force mechanism from the FSR pressure sensor to the computer as a stage for the development of smart footwear. The compressive force is necessary to enable us to analyze the walking patterns of the users of smart footwear. The concept is in line with the development of human-computer interaction to improve healthcare awareness among common people [9].

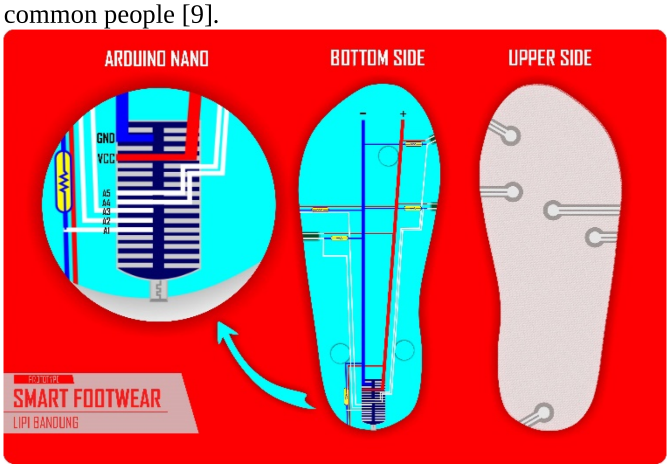


Fig. 1. The arrangement of the FSR pressure sensor and the Arduino Nano micro controller on the sandal.

There were several limitations to this study. The first was that the measurement instrument designed was confined to the electronic circuit and the equation function of resistance with force, not to integrate it into the prototype that had been made. The second was that the voltage divider circuit used only for one FSR pressure sensor. As such, to integrate this measuring instrument into prototypes that have been made, we need an electronic circuit that is able to measure the amount of voltage output from each sensor in each foot sole area simultaneously, without affecting the measurement of voltage output in other FSR pressure sensors. The third was that the FSR pressure sensor used was not known for its error specifications, so the calculation of error propagation was not possible. And the last was that due to the limitations, the force was applied manually with an analog force gauge, not by a compression testing machine.

II. Method

A. Research Framework

In the beginning, a manual measurement was performed by applying the compressive force using a force gauge to the FSR sensors, followed by reading the resistance value of the sensor with a multimeter. Measurements were made on the five FSR pressure sensors and in different magnitudes, from 5 N to 50 N with an increase of 5 N. Data were obtained, collected and processed using MATLAB software. The data were defined into two variables namely compressive force and resistance. The data were made in the form of vectors with dimensions n x 1, where n is the total amount of the data. Then, we entered the curve-fitting program in MATLAB by giving the cftool command in the MATLAB command window. In the curve-fitting tool, the x-axis was set as the resistance data and the y-axis was set as the compressive force data. The curve-fitting equation model that was chosen produced the most representative shape to the distribution of the acquired data. After that, we obtained the force function on the resistance and the coefficient value.

In the second stage, a simple Arduino electronic circuit was made to measure the source voltage. The step is then followed by making an analog voltage receiver program, followed by synchronizing the voltage received by Arduino. After that, testing was performed on the circuit by entering the known voltage value and checking the value being detected by the Arduino program. If the voltage matched the input value then we proceed to the next stage. On the contrary, if it had been different, then we return to the re-making stage of the Arduino circuit for source voltage detection.

The third stage was conducted by making a voltage divider circuit to detect the voltage on the sensor, accompanied by making a program to detect the voltage from the sensor. By using a voltage divider circuit, the output resistance value of the sensor can produce a large voltage on the sensor. The output voltage and the source voltage were then processed with the equation obtained in the previous step to get the force acting on the sensor. After the circuit and the program were finished, the tool was tested. Tool testing was performed by giving a certain compressive force with a force gauge, then the results of the force detection are displayed with the Arduino program. If it were considered acceptable, we would proceed to the recording stage. If there were a large difference then we would return to the programming stage and the sensor detection circuit, or return to the stage of collecting experimental data to obtain a new coefficient of function equation.

A voltage divider is an electronic circuit that is very commonly used. This circuit takes the higher voltage as the source voltage and converts it to a lower output voltage using a pair of resistors. The voltage divider circuit can be used to measure the magnitude of the resistance of one resistor used in the circuit by utilizing the difference in source voltage and output voltage [10]. The formula for calculating the output voltage is based on Ohm's Law. The formula for calculating the output voltage (V_{out}) in the voltage divider circuit can be seen in equation (1) below.

$$V_{out} = \frac{V_s \, x \, R_2}{(R_1 + R_2)} \quad (1)$$

Where:

- V_s = source voltage (volt)
- R_1 = first resistance resistor (ohm)
- R_2 = second resistance resistor (ohm)
- V_{out} = output voltage (volt)

In the last stage, we proceeded to make the report for the main experiment. The main experiment was performed in order to achieve the purpose of this study as stated in the introduction section.

B. Instruments and Materials

In this section we describe the instruments and materials used in the design of the pressure measurement device. The following instruments and devices were used: FSR pressure sensors (5 pieces), analogue force gauge, multimeter, electronic circuit breadboard, Arduino Uno, resistor 1 kOhm, wire/cable, USB to serial converter cable, Personal Computer (PC), Arduino software, and Matlab cftool.

Fig. 2. The labelled FSR pressure sensors that marked their placement.

The cftool MATLAB software was used to do curve-fitting and the Arduino software was necessary for writing and uploading programs/code to the Arduino board and to do force measurements [11][12]. The FSR pressure sensors (Figure 2) were used to produce resistance in accordance with the magnitude of the force exerted. A force gauge was used to apply the measured force to each of the FSR pressure sensors. A multimeter was used to measure the magnitude of the resistance change on the FSR pressure sensor after the force was applied. The breadboard and cable/wire were used to assemble a voltage divider circuit consisting of sensors and resistors. The Arduino boards were used to read the resistance and voltage values that occurred in the circuit. In order to connect the Arduino board to the computer to transfer the results of the FSR pressure sensors detection, a USB to serial converter cable was used.

III. Results and Discussion

A. Force-Voltage Output Relation in the Circuit

This section discusses the relation between the force and output voltage from the circuit acquired from the experimental data processing. As explained in the research methodology and depicted in Figure 2, the five FSR pressure sensors were used with the labels A, B, C, D, and E. The magnitude of the force applied to each FSR pressure sensor started from 5 N to 50 N with an increase of 5 N (i.e. 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 N). For each sensor and each force applied, an experiment was carried out twice, namely the first experiment and the second experiment to obtain many data points. Table I displays the results of this experiment. Sensor A (1) means using sensor A during the first experiment, sensor A (2) means using sensor A during the second experiment, sensor B (1) means using sensor B during the first try, and such condition also applies for the other three pressure sensors.

TABLE I.

Force-resistance data from the FSR pressure sensors in the first experiment

Force (N)	Resistance (100 kOhm)				
	Sensor A(1)	Sensor B(1)	Sensor C(1)	Sensor D(1)	Sensor E(1)
5	11.4	14.3	10.5	7.5	10
10	9.4	9	8.8	6.7	6.8
15	7.5	8.3	5.9	5.7	4.7
20	5.8	7.7	5.1	4.4	3.2
25	4.8	4.5	3.9	4	2.5
30	3.9	3.7	5.7	3.7	4.2
35	3.5	3.4	2.7	3.2	3.5
40	3.4	3.2	2.4	2.6	3.3
45	3.3	2.9	2.5	2.6	3.6
50	2.7	2.5	3.5	2.5	3.1

TABLE II.

Force-resistance data data from the FSR pressure sensors in the second experiment

Force (N)	Resistance (100 kOhm)				
	Sensor A(2)	Sensor B(2)	Sensor C(2)	Sensor D(2)	Sensor E(2)
5	13.4	17.5	7.9	11.1	9.3
10	11.7	12.6	7.7	6.3	7.1
15	9.2	11	5.7	5.9	5.7
20	5.4	6.3	4	5.1	5.4
25	4.6	4.9	4.3	4.5	4.5
30	3.8	3.4	2.7	3.9	4.2
35	3.2	3.2	2.3	3.5	3.8
40	2.9	2.9	2.5	2.5	2.7
45	2.9	3.2	2.3	2.5	2.7
50	3.5	3.7	2.5	3.1	2.6

After obtaining the sensor resistance force data as shown in Table I and Table II, then a scatter plot was made from the data. All Force (N) data were set as the y-axis and correspond to Resistance data (100 kOhm) which were set as the x-axis. After that, curve-fitting was performed using the MATLAB curve-fitting tool. The results are illustrated in Figure 3 and 4. Figure 3 shows the scatter plot as well as the curve-fitting results curve with the power model using the MATLAB curve-fitting tool.

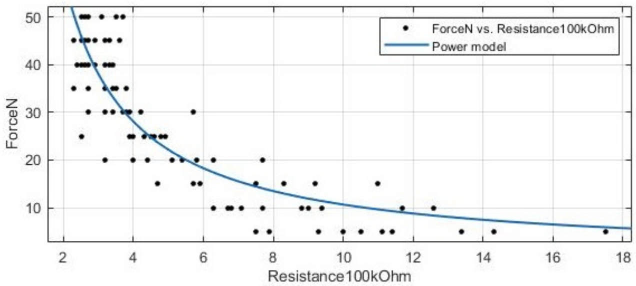
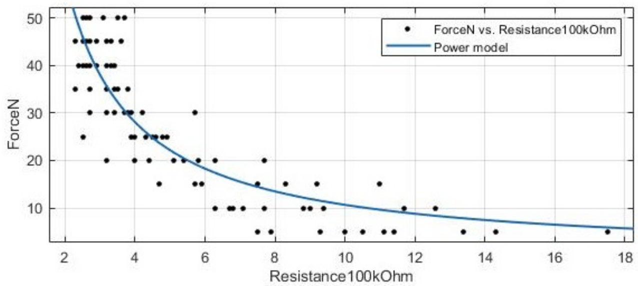


Fig. 3. Results of curve-fitting with power model (curve).



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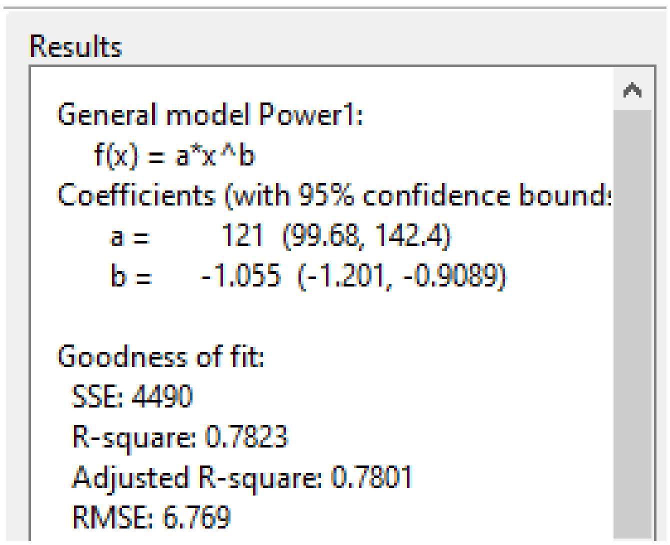

Fig. 4. Results of curve-fitting with power model (function).

The general form of the power function of this model can be seen in equation (2).

$$f(x) = a \times x^b \quad (2)$$

Where:

- a and b are coefficients with values that can be seen in Figure 4.
- f (x) is y (x), i.e. Force (N).
- X is the resistance (100 kOhm) of the FSR pressure sensor (or R_2)

From the three points above, the relationship between force and FSR pressure sensor resistance is obtained, as can be seen in equation (3).

$$F(R_2) = a \times {R_2}^b \quad (3)$$

Next, complete equation (1) in the method section for R_2, then use the equation to substitute R_2 in equation (3), so we will get the relationship between the force and the output voltage as can be seen in equation (4).

$$F(V_{out}) = a \times \left[\frac{V_{out} \times R_1}{(V_s - V_{out})}\right]^b \quad (4)$$

Where:

- V_s is the source voltage (volt)
- V_{out} is the output voltage displayed by Arduino
- R_1 is a constant resistance (1 kOhm)
- R_2 is an adjustable resistance which is the FSR pressure sensor (ohm)

Equation (4) is then changed to the Arduino code which is placed after the code to recognize the circuit output voltage. This code is then uploaded to the Arduino board so that the serial monitor in the Arduino software can directly display the force received by the FSR sensor in real-time. In the next section, we will explain the series of design results.

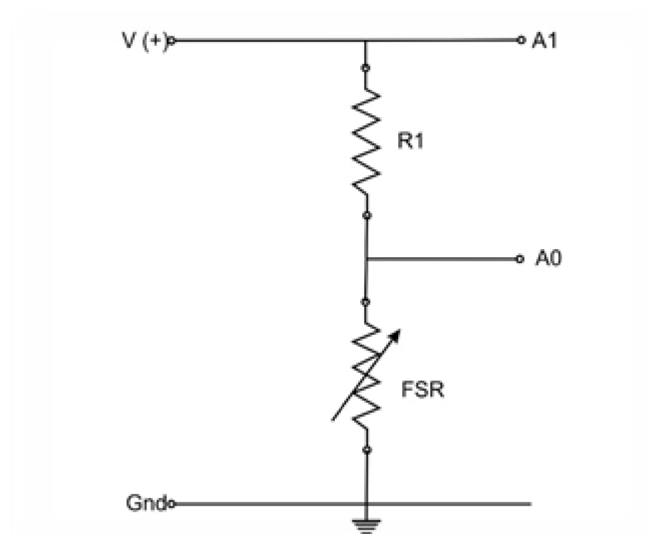

Fig. 5. Schematic diagram of the designed voltage divider.

B. Pressure Force Measuring Circuit

The voltage divider circuit scheme is shown in Figure 5. The circuit consists of two resistors. The R1 resistor is a constant resistor and the FSR resistor is an adjustable resistor. The resistance value on the FSR sensor will change according to the compressive force value received by the FSR sensor. This circuit has two inputs and two outputs. The input consists of a voltage of 5 Volt and Ground. While the output consists of a voltage corresponding to the input (A1) and a voltage that changes due to changing FSR resistance values (A0).

The overall set of design results including force gauge, FSR sensor, Arduino board, and the computer is shown in Figure 6. The workflow is as follows: the force gauge gives a measured force to the FSR sensor which results in changes in the resistance value of the sensor. Changing the FSR sensor resistance value will change the value of the output voltage in the circuit (A0). The output voltage (A0) is used as an Analog Input on Arduino Uno. The display of the value of the output voltage (volts) is changed by the equation of the force of the output voltage into a force value (N), as such, it becomes a force in real-time. Then the display on the computer (serial monitor menu in Arduino software) will recognize the magnitude of the force received by the FSR sensor in real-time.

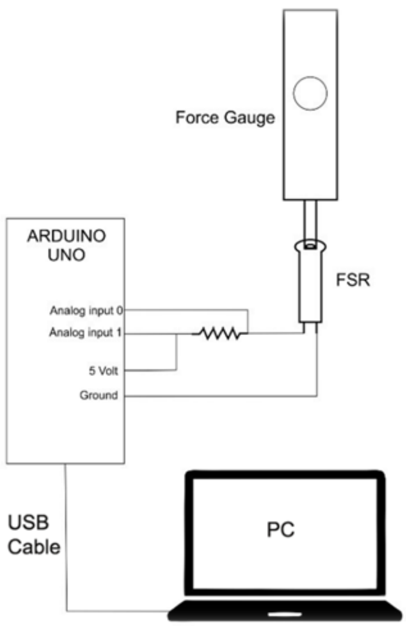

Fig. 6. Schematic diagram of the designed pressure measurement instrument.

C. *Force Measurement Validation with the Designed Measurement Instrument*

Validation was performed by giving a force of known magnitude (using a force gauge) to the FSR pressure sensor, then the magnitude of the force that was detected by the gauge is displayed on the computer. This validation was conducted to understand how great the error of this instrument is in measuring the compressive force. The magnitude of the force exerted with the force gauge was used as a comparison value.

TABLE III.

TEST RESULTS OF THE DESIGNED MEASUREMENT INSTRUMENT

Force Gauge (N)	Test 1 (N)	Test 2 (N)	Test 3 (N)	Test 4 (N)	Mean
5	6	5.75	4.2	5.1	5.26
10	10.3	11.6	9.7	11.5	10.78
15	14.5	12.2	14.8	15.4	14.23
20	19	19.8	19.8	18.7	19.33
25	23	24.5	24.9	22.5	23.73
30	29	31.5	29.8	27.4	29.43
35	32	35.7	35.7	29.75	33.29
40	37	40.57	39.7	32.5	37.44
45	39	41.2	44	34.5	39.68
50	41	41.6	30	35.6	37.05

Table III shows the testing results of the designed measurement instrument. The test was carried out four times for each force from 5 - 50 N with an increase of 5 N. From the test results data in Table III, an error calculation was performed for each test and for each given force, using equation (5), then the average error value was calculated.

$$Error\ (\%) = \left|\frac{F_{measurement\ inst} - F_{force\ gauge}}{F_{force\ gauge}}\right| \times 100\% \qquad (5)$$

Table IV shows the error size of the test results of measuring instruments that have been designed and their averages. From Table IV, it appears that the average minimum error is 3.4% and the maximum error is 25.9%. To facilitate visualization, scatter plot data is also displayed in Figure 7. Figure 7 shows a scatter plot of the distribution of the error of the compressive force test results using a measuring instrument that has been designed. From Figure 7, it appears that the largest error occurred at a force of 50 N, while the distribution of the smallest error occurred at 20 N.

TABLE IV.

ERROR TEST RESULTS OF THE DESIGNED MEASUREMENT INSTRUMENT

Force Gauge (N)	Error Test 1 (%)	Error Test 2 (%)	Error Test 3 (%)	Error Test 4 (%)	Mean Error (%)
5	20.0	15.0	16.0	2.0	13.3
10	3.0	16.0	3.0	15.0	9.3
15	3.3	18.7	1.3	2.7	6.5
20	5.0	1.0	1.0	6.5	3.4
25	8.0	2.0	0.4	10.0	5.1
30	3.3	5.0	0.7	8.7	4.4
35	8.6	2.0	2.0	15.0	6.9
40	7.5	1.4	0.7	18.8	7.1
45	13.3	8.4	2.2	23.3	11.8
50	18.0	16.8	40.0	28.8	25.9

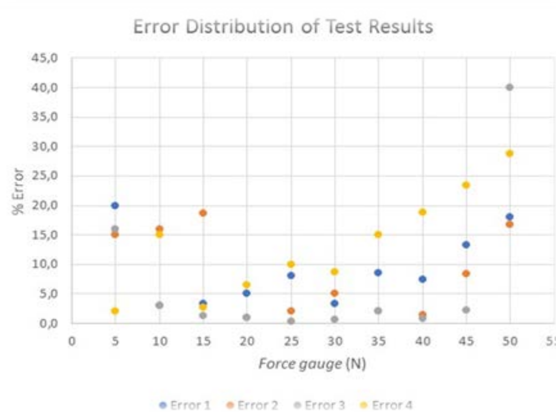

Fig. 7. Error distribution of test results of the measuring instruments that have been designed.

FSR sensor is a device with a material whose electrical resistance value can change when applied to the compressive force [13]. The advantages of this FSR are its minimalist size, low-cost and affordable, and good shock resistance. While the disadvantage of this FSR is that it has low precision, measurement results may differ by 10% and more than usual where the FSR capacitors have superior sensitivity and long-term stability but require more complicated drive electronics. Furthermore, a hot and humid environment such as in Indonesia has also been suggested to affect the fidelity of the measurement. Therefore, this type of study is necessary before the proliferation of the FSR pressure sensor in the package of various products such as smart footwear. Considering the effects of the environment on the sensor, a combination with a GPS based tracking system [14] or statistical approach [15] may mitigate the negative impact on its precision. The application of a linear quadratic estimation in the form of Kalman filtering to make any measurement adjustments for the predicted error is one suggestion for the next step of this study. Other methods may include the use of machine learning algorithm that allows the inclusion of environmental effects in the consideration of measurement [16].

IV. Conclusion

From this study, we may take the following conclusions. FSR pressure sensors have poor resistance to be applied to smart footwear. After a number of experimental data retrieval and validation, it was visible that the five sensors used were damaged (delamination in the plastic spacer), which affected the measurement results. Because the force detection by the FSR pressure sensor is strongly influenced by the angle formed between the active area of the sensor and the direction of the force coming, it is best if the force applied is done perpendicularly. However, in smart footwear, the force given by the user's feet is continuous and it is not always perpendicular. Validation results show the average error of this measuring instrument varies from 3.4% - 25.9% depending on the force given the condition of the FSR pressure sensor used.

If higher accuracy is required in force measurement, there are several suggestions to be considered. The applied force when collecting experimental data was conducted with a force gauge that has a mounting so that the angle of force applied to the active area of the sensor is perpendicular. This was intended to generate a better coefficient of drag-force relationship. In addition, we also recommend using a self-designed clamp that has the same area as the area of the active circle on the sensor. The clamp intended here is the force gauge head that is in direct contact with the FSR pressure sensor. It is also better to use FSR pressure sensors with better quality, especially new FSR sensors when validating the data. In addition, the FSR sensor is only suitable for use if there is no need for high accuracy in force measurement, such as the requirement to only measure the relatively larger or smaller force, or to see the force patterns acting on the smart footwear.

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