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Abstract— **This paper presents a characteristic of a 32x32 sensor matrix based on velostat for foot pressure distribution measurements. The sensor has been constructed of dual electrodes placed on the top and underneath velostat as the sensing material. The experimental results show the sensor matrix has relatively linear in Force-Conductance response until 15 N. The system evaluation stage was obtained by comparing the sensor matrix with several other methods implemented in RSON and obtained the performance of the sensor matrix in the form of the comparison of the footprint area with the error value of 7.3% to 68.8%, the average pressure of 7.3% to 68.8%, the maximum pressure 37.6% to 70.7%, body weight of 0.4% to 12.1%, and arch-index with a specificity value of 0.3 and a sensitivity of 0.5.**

Keywords—Velostat; Pressure Sensor Matrix; Crosstalk

I. INTRODUCTION

The distribution of human plantar pressure data reflect conditions associated with the foot, such as foot structure, function and control the posture of the whole body and others. Human foot pressure distribution measurement can provide vital information and very useful for medical diagnosis. One mayor that has attracted considerable attention by researchers in biomedical and sport related applications is an analysis of foot plantar pressure distribution to reveal the interface pressure between the foot plantar surface and shoe sole.

The most common pressure sensors are capacitive sensors, resistive sensors, piezoelectric sensor and piezoresistive sensor. Capacitive force sensors are usually a parallel-plate capacitor, which changes its capacitance in function of the applied force. This is due to the dielectric that, in this case, is an another sort of squeezable material that gets thinner when subject to pressure[1]. The advantages of capacitive sensors are high accuracy, Flexible, durable. However, the conditioning circuit and computation are complexes[2]. Piezoelectric force sensors are based on the piezoelectric effect of some materials, which generate an electric charge when stressed. The most suitable material for clinically oriented body pressure measurement is polyvinylidene fluoride (PVDF). These flexible materials can be used to sense force or pressure but it is sensitive to many factors (i.e., bending, temperature)[3]. Piezoresistive/force sensing resistors instead have the advantages that can be fabricated using flexible materials, but also they are very robust against noise and the conditioning electronics is simple, that in many cases only a bias resistor is used[4].

One of the most widely used sensors in the application of plantar pressure is the force sensing resistor (FSR). Force Sensing Resistor (FSR) is an analog sensor that function to change the compression force to change the resistance, when given the force on the FSR, the resistance will decrease. FSRs are made of a conductive polymer that changes resistance with force, applying force causes conductive particles to touch increasing the current through the sensors. The advantages of FSR are high spatial resolution and flexible where FlexiForce A301 has range from 10-110.000 N with 0.5 inch diameter[5]. The advantages besides having high spatial resolution and flexible, the resistive sensor is also low-cost. Many researchers have conducted measurements of pressure and posture analysis using the FSR sensor design results, specification and signal conditioning designs according to application needs.

Del Prete et al.[6] pressure measurement in analyzing in the nature of metrological for static and dynamic measurement conditions, the result of design using an 8×8 matrix array of pressure sensors Novel (velostat) and the result of pressure from the system design of 0-5000 kPa. D. Giovanelli et al.[2] implemented in a wearable technology, using FSR sensor with the resistive material (velostat) for pressure measurement. Lin and Seet [7] using a 10 mm×10 mm textile pressure sensor to be implemented in pressure measurement with 0-1000 kPa pressure design results. This paper presents a characterized by velostat sensors, implementation, and evaluation of appropriate system platforms for foot pressure distribution measurements.

II. SENSOR DESIGN

The platform system is designed with a 32×32 matrix and each sensor size is 7mm×7mm with a distance between sensors is 1cm to avoid a short circuit between sensors. The sensor is constructed of three main layers which are a top electrode, velostat, and bottom electrode respectively.

Sensor matrix is controlled by the microcontroller to scan every single sensor one by one using multiplexer. Unfortunately, this setup is causing leak current to others sensor while scanning specific sensor (cross-talk). It's mean others sensor value could affect the scanned sensor.

To avoid cross-talk, the current barrier is applied to every sensor. To achieve this setup, double layer PCB is used as a non-conductive layer to connect the top electrode to a diode which can simplified manufacturing process.

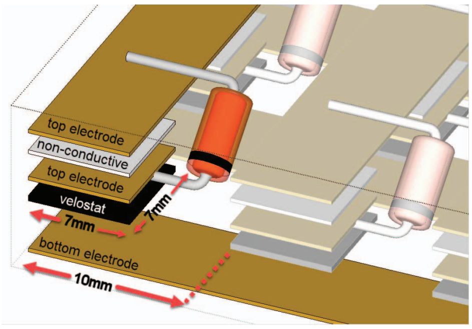

Fig. 1. Three main layers of sensor matrix

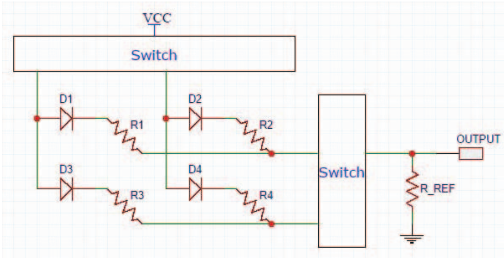

Fig. 2. Current barrier to avoid cross-talk

III. Calibration

Sensor calibration is done by measuring force to output voltage response. To get an overview of the system response, use samples as 8x8 (64 samples) with interval 4 sensors in each row and column. This sampling shortens the working time yet still get the representative of the system response from each part of the sensor matrix.

The instrument for calibration is a balance weight set which has range 1 to 15 N with interval 1 N. In this experiment the sensor matrix has been placed on a flat surface. Since this matrix is hand-made and the electrode has a relatively small size, the sensor matrix thickness is not strictly uniformed. By placing the fabric (soft and non-conductive) as a cushion between the balance weight set with the sensor matrix, the force on the sensor matrix can be spread evenly.

Output value has been measured 30 seconds after load application to make sure voltage measurement in steady state. The sensor calibration curve has been measured by converting 10bit ADC value to resistance by the following equation:

$$R_{(velostat)} = R_{(reference)} \frac{1024 - V_{(ADC)}}{V_{(ADC)}} \qquad (1)$$

Where V(ADC)=10 bit ADC value, R(reference)=resistor reference on voltage divider, and R(velostat)=sensor matrix resistance.

The time response has been measured for a 15N step unit. There is no response delay observe and the time response is 350-350ms as shown in figure 3.

The Force-Resistance and the Force-Conductance curve are obtained by averaging the entire sample value (64 samples). The Force-Conductance curve which sensor matrix conductance can be calculated by the following equation:

$$G_{(velostat)} = \frac{1}{R_{(velostat)}} \qquad (2)$$

Where G(velostat)=sensor matrix conductance.

Figure 4 shows the wide deviation of the sensor sample. The pattern has been searched for the cause of the sample sensor wide deviation value. But no pattern can be represented by the random form of the deviation. Therefore this wide deviation value is possible because it is the influence of hand-made manufacturing.

Although deviation of 64 samples on sensor matrix is wide, it percentage tends to reduce as the force increases. This evidance has been shown in Figure 5 which illustrates the relationship between the two. Its mean, this hand-made sensor matrix more realible to sense high force than low force.

Measurements show that the sensor matrix has most likely power-equation relation in Force-Resistance and relatively linear-equation in Force-Conductance response until 15 N, which can be modeled by the following equations:

$$F = \left(\frac{6689.68}{R_{(velostat)}} \right)^{\frac{1}{0.88}} \qquad (3)$$

$$F = 8879.18 G_{(velostat)} - 0.76 \qquad (4)$$

Where R(velostat)=sensor matrix resistance, G(velostat)=sensor matrix conductance and F=applied weight force.

From the equations, we get the Square Error value of equation 3 and equation 4 is 1.84 and 0.93 respectively. Based on this, it is found that the relationship between conductance and compressive forces has a smaller Square Error value. Also in equation 4, the relationship between the two is linear where it is simpler compared to the relationship in equation 3.

The median filter is used in this system to reduce the noise. But with this pressure with a small surface area becomes unreadable by the system. Given the area of the object to be used has a size larger than the sensor cell size on the sensor matrix then this is not a problem. By using the median filter we get the following matrix sensor outputs.

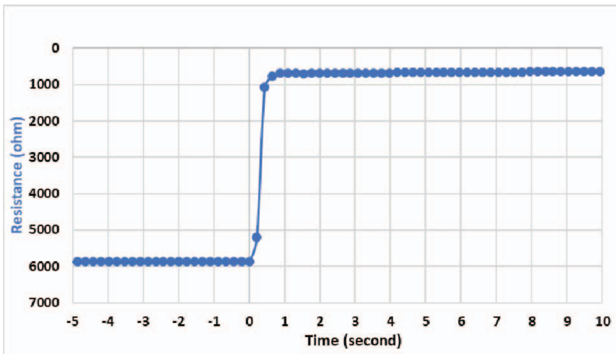

Fig. 3. The sensor output response during a 15 N step loading

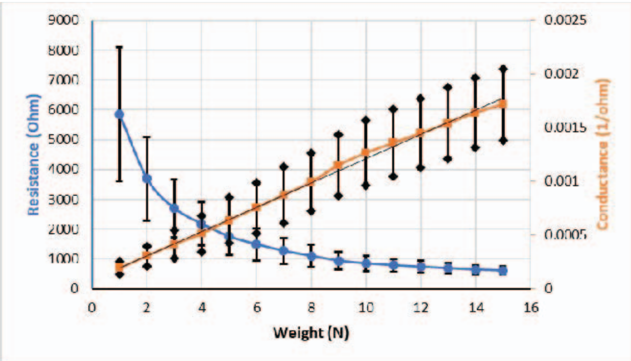

Fig. 4. Force-Resistive and Force-Conductance characteristic of sensor matrix. Deviation is representation of 64 samples sensor

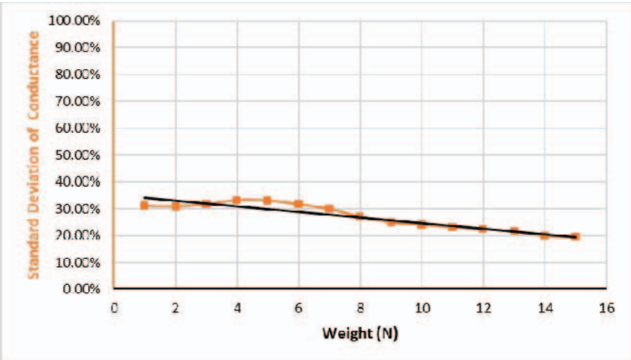

Fig. 5. Force-Standard Deviation of Conductance characteristic. Deviation is representation of 64 samples sensor

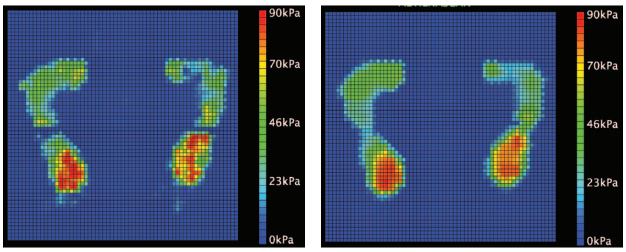

Fig. 6. Before and after median filter applied to the resuld of sensor matrix velostat

IV. Experiments and Results

Comparisons to other measurement methods were performed to test the overall sensor matrix. The test is performed in RSON (Rumah Sakit Olahraga Nasional) by comparing the results from the matrix sensor with three other methods which are Scale, PEDOSCAN, and a footprint measurement using ink and paper. The compared outputs are maximum pressure, average pressure, surface area and arch-index. The output of each method are as follows:

TABLE I. THREE OTHER MEASUREMENT METHODS TO EVALUATE SENSOR MATRIX VELOSTAT

Instrument	**Area**	**Average Force**	**Total Body Weight**	**Max Force**	***Arch-index***
Sensor Matrix Velostat	✓	✓	✓	✓	✓
Footprint (Ink and Paper)	✓	✗	✗	✗	✓
PEDOSCAN	✓	✓	✓	✓	✗
Scale	✗	✗	✓	✗	✗

Where,

✓ = Gold Standard Measurement
✓ = Tested
✗ = Untested

The test was conducted using 10 people who have weight between 40 kg to 100 kg. The selection of body weight above 40 kg is done to get the high pressure value of the sole of the foot to be read by the matrix sensor, while the selection of body weight below 100 kg to keep the matrix sensor from the possibility to be damaged. The measurement is done 3 times to obtain a value close to the true value of the output of each method. As for the measurement of ink and paper footprint using only 1 time in accordance with the procedures in RSON.

Fig. 7. The comparation of the result (area, average pressure, total body weight, maximum pressure, and arch-index) from four measurement methods

V. Discussion

The footprint surface area is the contact area of foot while in standing position. From Fig.7, it can be seen that the surface area using PEDOSCAN is much higher than the footprint method. The difference that occurs is 61.7% to 158.6%. this happened because the upper surface of PEDOSCAN has a foam-like property. It is possible this large difference value because the footprint method is done on a flat and rigid surface (floor), whereas in PEDOSCAN the foot sinks on the surface of the foam causing contact between the PEDOSCAN with the foot to become wider. The sensor matrix is also the measured higher than the footprint method. However, the value of the difference is not as high as PEDOSCAN is 7.3% to 68.8%.

The average pressure is the average pressure of the foot. By comparing the mean pressure of the PEDOSCAN with the matrix sensor then seen in Fig.7 the measurement have consistency of both methods. Where when the PEDOSCAN shows the average left foot pressure value greater than the right foot, the matrix sensor also shows the same thing and when the mean left foot pressure value is less than the right foot, the matrix sensor also shows the same thing.

The interesting thing has shown in the weight-loss measurement, where its value is related to the average footing and pressure. By using the weight scale we get the weight of each respondent which is then compared with the output of the PEDOSCAN and the sensor matrix. The output of PEDOSCAN has a value above the weight scale with a difference of 30.9% to 60.6%. while the sensor matrix only has a difference of 0.4% to 12.1%. This shows that the PEDOSCAN in RSON can not be used as a reference in taking weight data because the value is too far compared to weight scale as gold standard weight measurement.

The maximum pressure is the highest pressure of foot. In Fig.7, the result difference of the two methods is very far, where the PEDOSCAN can reach 29.7 N/cm^2 but the sensor matrix only reaches 8.9 N/cm^2. This might be caused by imprecise reading of PEDOCSAN. But because the result difference of the two methods is too far, it may be due to other factors.

Arch-index is the index of curvature of the foot obtained by calculating the area of 1/3 the middle of the foot divided by the surface area where the area of the toe is not included in the calculation which is divided into three categories, high arch for arch-index <0.21, normal for arch-index 0.21 to 0.26, and flat foot for arch-index> 0.26.

TABLE II. The Arch Index True Condition From Sensor Matrix Velostat Calculation Compared To Footprint Method

Respondent	Footprint		Sensor Matrix		True Condition	
	Left	Right	Left	Right	Left	Right
Respondent 1	Normal	HighArch	HighArch	Normal	**F(-)**	**F(+)**
Respondent 2	FlatFeet	Normal	HighArch	HighArch	**F(-)**	**F(-)**
Respondent 3	Normal	FlatFeet	Normal	Normal	**T(+)**	**F(+)**
Respondent 4	Normal	Normal	FlatFeet	FlatFeet	**F(-)**	**F(-)**
Respondent 5	Normal	Normal	Normal	Normal	**T(+)**	**T(+)**
Respondent 6	FlatFeet	FlatFeet	FlatFeet	FlatFeet	**T(-)**	**T(-)**
Respondent 7	HighArch	HighArch	Normal	Normal	**F(+)**	**F(+)**
Respondent 8	Normal	Normal	Normal	HighArch	**T(+)**	**F(-)**
Respondent 9	HighArch	Normal	FlatFeet	HighArch	**F(-)**	**F(-)**
Respondent 10	Normal	Normal	Normal	Normal	**T(+)**	**T(+)**

Based on table asdf, specificity and sensitivity can be calculated with this formula:

$$Specificity = \frac{T(-)}{T(-)+F(+)} \tag{5}$$

$$Specificity = 0.3 \tag{6}$$

$$Sensitivity = \frac{T(+)}{T(+)+F(-)} \tag{7}$$

$$Sensitivity = 0.5 \tag{8}$$

VI. Conclusion

Although deviation of 64 samples on sensor matrix is wide, measurements show that the sensor matrix has relatively linear-equation in Force-Conductance response until 15 N and has Square Error Value=0.93: By comparing the sensor matrix velostat with other methods, the result of sensor matrix is closer to weight scale than PEDOSCAN. However, sensor matrix velostat still cannot replace footprint method for calculating arch-index due to sensitivity and specificity are too low.

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