CHAPTER 7

DIABETIC FOOT PLANTAR PRESSURE MONITORING SYSTEM USING FORCE SENSITIVE RESISTOR SYSTEM

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7.0 INTRODUCTION

Many people are suffering from diabetes; it was the major cause that has led many to hospitalization. According to [1], patients with Type 2 diabetes suffering from peripheral neuropathy are at high risks of developing diabetic foot syndrome, which leads to foot ulcerations that caused mainly by high peak plantar pressures. Without early prevention and intervention [2], diabetic foot ulcer has 15 times greater risk to cause lower limb amputation. Therefore, further studies on early prevention may help in healthcare management.

Early prevention of diabetic foot ulcer is viable by inventing a sensing technology device to obtain information on the interface pressure between foot plantar surface and a sensor [3]. It is used to monitor the foot plantar surface pressure by taking the advantage of current technology. The plantar pressure measurement system can be classified into two groups: platform system [4] and in-shoe system [5]. Examples of pressure monitoring system available today are Fiber Bragg Grating (FBG) based foot pressure monitoring pad [6] and pressure sensing shoe insoles [7] using piezoelectric (PZT) [8], resistive (FSR) [9], and capacitive [3] sensor.

Among all these products, the FSR was widely chosen for the sensing part. The working principle of this element is based on the
changes in conductive resistance formed between two electrodes with the application of force or pressure [9]. The resistance decreases if pressure is applied, while current flow would increase [2]. According to [4], conductive polymer is a material for this sensor and its resistance change with the force applied [10]. Other function of this sensor include its ability in tilt-sensing, which is static acceleration of gravity and dynamic acceleration resulted from motion, shock or vibration [11]. An example of FSR in Figure 7.1 can hold weight until 10 kg. The square shape model of FSR would be required for higher weight. It would help practitioners to understand the mechanism of the ulceration, and provide a way for early detection or even prediction of diabetic foot ulcers [12].

![Image: Force sensitive resistor (FSR)](image)

Figure 7.1: Force sensitive resistor (FSR)

### 7.1 DIABETIC FOOT ULCER

Patients who have higher blood sugar level could lead to blood vessels and nerves damage. In this case, they may be unable to experience any sensation from their peripherals; these are typical in lower extremities such as feet. Foot ulcers shown in Figure 7.2 are the most widely recognized therapeutic conditions for patients with diabetes, with an expected rate of 12-15% among all people with diabetes [13]. Neuropathic and vascular changes in patients with diabetes mellitus placed them in danger after minor trauma or after pressure has prompted a breakdown within the integrity of the pores and skin, which would progress into the chronic foot wounds [2].
Diabetes Mellitus remained as a standout amongst the most predominant infections with an aggregate of 347 million patients around the world [11]. The determination of diabetes mellitus is via a fasting blood glucose test result of more than 6.7 mmol/l or random glucose of higher than 10 mmol/l [14]. Diabetes Mellitus patients have higher risk to have multiple complication especially foot ulcer. When diabetic foot wound was inflicted, there is an increased risk of ulcer developing, prompting contamination, gangrene, amputation, and even demise if important care is not being taken [14]. Foot care is a critical part of the care of the diabetic patient as a small ulcer may have hastily developed and threaten the viability of the foot itself [15].

7.1.1 Development of a Foot Ulcer

The combination of insensitivity and high pressures applied to the foot plantar of a patient placed a high risk of neuropathic ulceration that can lead to altered loading under the foot while standing and walking [16]. This development starts from minor trauma that can be seen from the Figure 7.3 that shows that the courses of getting foot ulcer, for example from ill-fitting shoes, abnormal walking pattern, walking barefoot or an acute injury [17].
The small injuries that healed slowly is the meaning of capillary closure within the skin. This small injury has always gone unnoticed, and left untreated, as there is a loss of pain sensation compounded by poor visual perception. Due to the unnoticed and untreated wound, the risk increased rapidly to bacterial infection because of poor circulation that leads to a slower respond to all treatment.

Reactive thickening of skin can be caused by abnormal load when motor neuropathy affects the muscles for normal foot movement and alters the distribution of forces during walking. Neuropathic ulcer happened due to the tissue ischaemic necrosis beneath the callus breakdown the skin and subcutaneous tissue as shown in Figure 7.4 [18]. Microcirculation dysfunction happened following the reduce of the blood distribution when arteriolar venular shunts and tissue ischaemia [19]. After that, the peripheral nerve function, which controls the blood flows through arteriolar vessels, would be affected. Dislocation or collapse of joints or bones of the foot would then happen and it leads to slight trauma that triggers fracture of weakened bone by increase adjacent bones load until serious destruction, which is a secondary ulceration [20].
7.2 FORCE SENSITIVE RESISTOR SENSING SYSTEM

This study aims to develop diabetic foot plantar pressure monitoring system, which can be used by a diabetic patient who wishes to continuously monitor the pressure at his/her foot plantar to avoid the incidence of foot ulcer. This can also be used by those who have incorrect standing posture because the latter may produce non-uniform force on the foot plantar. They also have higher risk of getting foot ulcer. Through this system, it can be used to sense and analyze the pressure from the foot plantar when people are standing on the FSR sensor. Therefore, providing the early prevention mechanism of foot ulcer.

This work began testing the performance of the FSR sensor, which is used to convert the measured pressure into voltage. From the acquired voltage, Arduino was used as the microcontroller to process the data and analyze these inputs before identifying input with the highest voltage. This is because the highest voltage corresponds to the point with the highest force. The Arduino would alert its user through the virtual output display. All LEDs on the plantar foot platform would turn on while the virtual heel display would show ‘NO PRESSURE’ if all sensors detected no pressure. However, if one input sensor gives the highest voltage reading compared to others, the associated LED would light up and virtual display showed ‘HI PRESS @ A, B or C’. This process would continue as long as force is detected. The flow of the sensing processes is shown in Figure 7.5.
7.2.1 Phantom heel platform and virtual heel display

Figure 7.6 shows the phantom heel platform that has FSR sensors installed; Arduino Uno would process and analyze the detected signals while wi-fi module is to transmit data wirelessly to the phantom heel virtual display. In this work, heel platform used three sensors placed at three different points shown in Figure 7.7. It was hypothesized that point 3 has the highest risk of getting foot ulcer; this is followed by point 2. Point 1 has the lowest risk.
After an object was placed on the sensors, voltage readings based on the force applied were sent to the Arduino. The latter was used to process and analyze the all voltage reading. The analyzed result was transmitted wirelessly to the phantom heel virtual display via wi-fi module. This phantom heel virtual display serves as an alert system by producing visualization on the location of point with the highest pressure.

This alert system is through the indication provided by LEDs. The LED of a specific point with the detected highest pressure would light up to notify the user. Operation of this system can be clearly
understood from Figure 7.8. From this, the user can take early prevention to reduce the pressure such as by changing their standing posture and special care in taking care of the wound at the specific location.

**Figure 7.8: Block diagram of system**

### 7.3 SYSTEM PERFORMANCE ASSESSMENT

The testing of the performance of the developed system is by placing object of uniform weight and object of different weight on the sensor. The main reason of not recruiting human subject is because each FSR sensor can only hold maximum weight of 10 kilogram (kg). Since objects of the same weight would produce the same voltage reading on all sensors, the investigations involved combinations of objects of different weights. Therefore, when a different weight is placed on the sensors, one point would hypothesize to have a comparatively higher force (hence larger voltage value) due to the higher pressure applied.

#### 7.3.1 System Accuracy and Repeatability

The performance of the developed system was evaluated prior to the measurement. Figure 7.9 shows the five objects used to test this system.
Figure 7.9: Objects used in the evaluation of system performance

A range of tests has been conducted to compare the weight reading between a conventional scale and FSRs used in this study. For the measurement of weight using FSR, voltage reading was interpreted into force by referring to the given datasheet, before it was converted into kilogram (kg).

The weight reading of the objects shown in Figure 7.9 measured via weighing scale and FSR. For each object, five readings were consecutively collected. The mean and standard deviation of the measurement is calculated and tabulated in Table 7.1, which showed a slight difference in the measurements. Since the reading from weighing scale was used as the gold reference, the mean difference of 0.09 kg shown in Table 7.1 is likely due to the limitation in the size of active area of FSR sensor and the position of object on the sensor. It must also be mentioned that there is high repeatability in the reading obtained via FSRs system, which mean standard deviation value is calculated as $\pm 0.03$. 
Table 7.1: Average weight of objects

<table>
<thead>
<tr>
<th>Object</th>
<th>Average weight using scale (kg)</th>
<th>Average weight using FSR (kg)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object 1</td>
<td>0.42 ± 0.01</td>
<td>0.35 ± 0.03</td>
<td>0.07 ± 0.02</td>
</tr>
<tr>
<td>Object 2</td>
<td>0.85 ± 0.02</td>
<td>0.75 ± 0.03</td>
<td>0.10 ± 0.01</td>
</tr>
<tr>
<td>Object 3</td>
<td>1.67 ± 0.01</td>
<td>1.54 ± 0.03</td>
<td>0.13 ± 0.02</td>
</tr>
<tr>
<td>Object 4</td>
<td>1.34 ± 0.01</td>
<td>1.25 ± 0.02</td>
<td>0.09 ± 0.01</td>
</tr>
<tr>
<td>Object 5</td>
<td>1.02 ± 0.01</td>
<td>0.97 ± 0.03</td>
<td>0.05 ± 0.02</td>
</tr>
</tbody>
</table>

Mean difference: 0.09 ± 0.03

7.3.2 System Reliability Performance

Meanwhile, the reliability of the system was tested through the repeatability in results obtained from a number of the test cycles. This was done by placing different combination of objects shown in Figure 7.9 on the developed plantar pressure monitoring system. The activation of LEDs observed in the Blynk application such as that shown in Figure 7.10 was tabulated in Table 7.2, where value ‘1’ indicates blink while otherwise is true for the value ‘0’. The virtual LCD notified its user by displaying ‘HI PRESS @ A’ when the LEDA lighted up, the same applied to LEDB and LEDC. When all LEDs ON, it would display ‘NO PRESSURE’.

Table 7.2: Reliability performance of system

<table>
<thead>
<tr>
<th>Exp. No.</th>
<th>Object weight (kg) (Position A,B,C)</th>
<th>Virtual platform (LED A, B,C)</th>
<th>Virtual LCD HI PRESS @</th>
<th>System reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.02, 0.85, 1.34</td>
<td>1, 0, 0</td>
<td>A</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>1.02, 0.85, 1.34</td>
<td>0, 0, 1</td>
<td>C</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>1.02, 0.85, 1.34</td>
<td>0, 0, 1</td>
<td>C</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>1.34, 0.42, 1.67</td>
<td>0, 0, 1</td>
<td>C</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>1.34, 0.42, 1.67</td>
<td>0, 0, 1</td>
<td>C</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>1.34, 0.42, 1.67</td>
<td>1, 0, 0</td>
<td>A</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>0.42, 1.02, 0.85</td>
<td>0, 1, 0</td>
<td>B</td>
<td>Yes</td>
</tr>
</tbody>
</table>

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Based on the result in Table 7.2, the reliability, $R$, of this system is calculated as 80% based on the following equation:

$$R = \frac{TP}{TP + FP} \times 100\%$$  \hspace{1cm} (1)

where TP and FP denote true positive and false positive, respectively. There were three of fifteen experiments giving false outcome. This is likely because of the position of objects that was not evenly placed on the sensor due to its comparatively larger size than the FSR sensor active area.
REFERENCES


