A WEARABLE DYNAMIC FOOT PRESSURE MEASUREMENT SYSTEM

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Abstract - Diabetic Foot Ulcer (DFU) is a complication of diabetes; this causes impaired mobility and even death. Higher rate of DFU occurrence adds huge burden on the healthcare system and billions are spent healing the wound. There is a need for reliably measuring dynamic foot pressure so that the users who are at a risk of DFU can be given feedback in real time to help them avoid DFU. We are developing a dynamic foot pressure measurement system in house to provide full coverage of risk foot areas and can measure up to 100 channels of dynamic pressure. In this paper we present a miniature 12 channel dynamic foot pressure measurement system consisting of an analog front end, an MCU based data acquisition moduleand a sensorized sock. This system can measure, analyze and store dynamic foot pressure data and feedback to the user in real time through on board aural and visual indicators. It can also optionally push the collected data to the back end server through a wireless link. Sensorized sock was fabricated by embedding off the shelf Force Sensitive Resistor (FSR) elements on the sock and wired up using conductive threads to form an array. Non-Inverting Op-Amp Circuit on board analog front end converts the resistance variations of the pressure sensor into avoltage which is then converted to digital using an on chip ADC of the MCU. MCU further analyzes the data and activates alarms when the detected pressure values exceed preset threshold values. The pressure measurement range of this systemis 100– 600Kpa with targeted accuracy of +/-2% and the scanning rate is 10 fps.

Keywords - Diabetic Foot Ulcer, Dynamic Foot Pressure, Sensorized Sock, Force Sensitive Resistor (FSR), Op-Amp.

I. INTRODUCTION

The Diabetic Foot Ulcer (DFU) is a clinical condition that has huge medical and economic burden on to individuals and the health care system[1][2].

In spite of this still there are no reliable schemes or methods to prevent this adequately. About ~382 million people suffer from diabetes globally [3] and this number is increasing rapidly. As per the National Health Survey (2010) in Singapore about 29.1% people in the age group of 60-69 had the diabetes and this proportion is expected to increase further.

DFU is a major complication of diabetes which causes morbidity, disability and even death. Loss of sensation of the foot due to diabetes (Neuropathy) and foot deformity are the two major causes of DFU[4][5][6]. But the fact is that the DFUs are preventable. In recent years, it has been shown that the DFUs can be prevented in diabetic individuals with neuropathy by doing objective pressure measurements [7][8] on the foot. Now the focus is being shifted to data driven prevention of DFUs from the treatment of developed DFUs[9].

Hence there is a need for a system which can measure and provide feedback to patients to substitute for their lack of sensation. Such system would allow the patients to respond to the high regional foot pressure and prevent DFU development. In this work we present a dynamic foot pressure measurement system which can measure the foot pressure with a sensorized sock and provide aural and visual alerts to the user

II. SYSTEM DESIGN

Design of wearable dynamic foot pressure measurement system should consider the following design constraints. It should be less intrusive to the user's daily routine and reliable. It should have provisions for analyzing the pressure data and configurable feedback to the user. It should also have an option to pull out the locally collected data wirelessly without interfering with user's routine. It should have a rechargeable battery of sufficient capacity to last for about a month.

The design of this system consists of the following modules as shown in Fig.1.

a) Pressure Sensing Element,
b) Wearable sensorized sock,
c) Analog Front End,
d) Miniature Data Acquisition module
e) Power management module

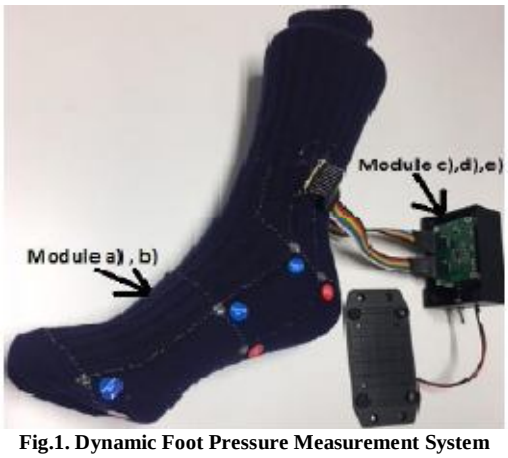


Fig.1. Dynamic Foot Pressure Measurement System

Modules a) & b) to gether forms a wearble sock worn by the user and modules c),d) and e) are enclosed in a miniature plastic enclosure and can be mounted on the users leg with a magnetic strip.

1.1. Pressure Sensing Element

Selection of pressure sensing element plays a main role in the performance of the foot pressure measurement system. We have tried various off the shelf Force Sensitive Resistor (FSR) sensors available in the market and found FS400 from the Interlink has the suitable pressure measurement range[10].

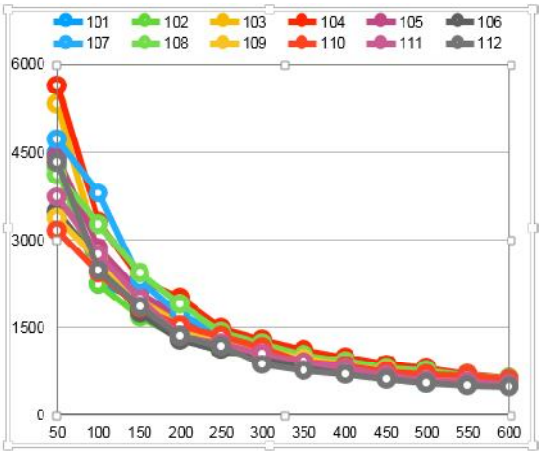


Fig.2. Pressure (Kpa) Vs Resistance Variations for 12 sensors measured

Typical resistance variation of FSR400 for an applied force is as shown in the Fig.2 for a set of 12 sensors and the measurement results were repeatable. From Fig.2we can see the non-linearity of the sensor response in the intended measurement range. This issue is further compounded when converting it into a voltage variation using and Op-Amp circuitry. This requires that the sensor response to be fitted using an optimal piecewise linear approximation such as quadratic equation. This can be easily done using an excel chart which can calculate the polynomial which can best fit the measurement data.

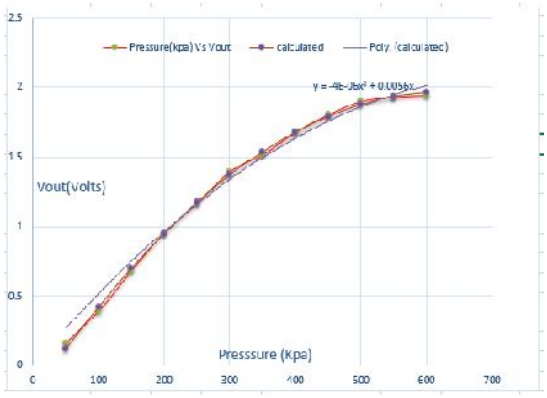


Fig.3. Curve Fitting of the Sensor Data

Fig.3. Show the response of the FSR after fitting using quadratic equation. Computational complexity in applying the quadratic equation in actual implementation is overcome by implementing a lookup table in the MCU firmware.

1.2. Wearable Sensorized Sock

Sensorized sock was designed using readymade school socks and the sensors are glued to the sensor positions using a glue after their tails are trimmed. Connection to the sensor elements made using the conductive threads to form a 3x4 sensor array as shown in Fig.4 and Fig.5



Fig.4. 3x4 FSR sensor Array in the Sock

Fig.5. shows the schematic representation of the 3 x 4 sensor array.

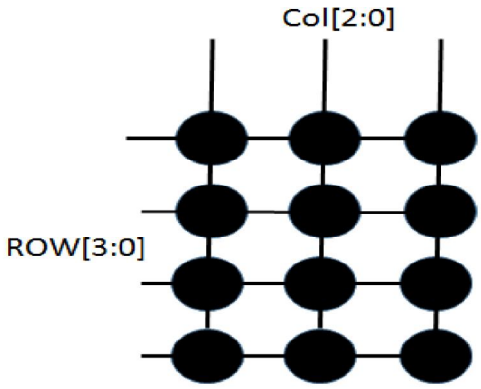


Fig.5. 3x4 FSR based sensor Array in Sock

Pressure sensor positions are defined based on the inputs from clinicians and there are 12 sensor positions defined as shown in Fig.6.

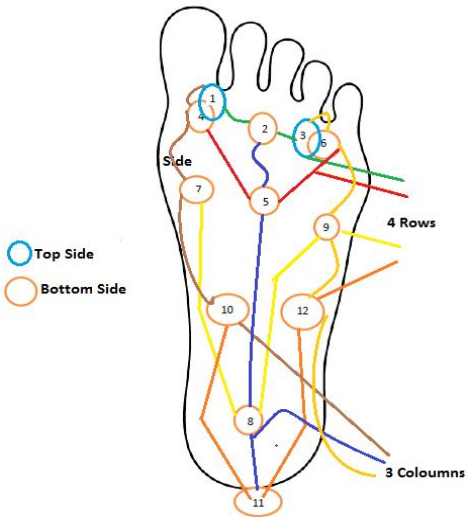


Fig.6. 3x4 FSR sensor Positions on the Sock

In future there are plan to increase this number up to 100 as the electronics can support up to 100 channels

1.3. Analog front End

Core of the multichannel analog front end is an array of 10 non-inverting Op-Ampsas shown in Fig.7which converts the resistance variations of the FSR400 sensor into a voltage output which is compatible with the ADC input range of 2.5V. There are two 16 channel analog multiplexers available on board and there are four control signals given to the multiplexer, but only 10 out of 16 channels used.

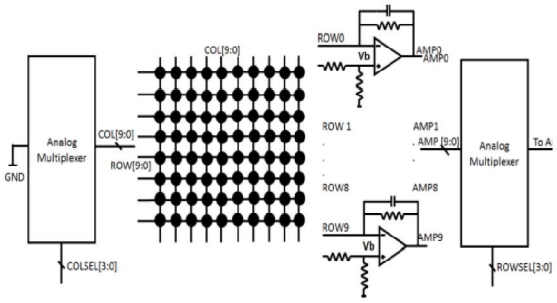


Fig.7. 100 Channel Analog Front End

The FSR400 is connected to the inverting terminal of the op amp and the other end is selectively grounded using an analog multiplexer to measure the resistance variations.Column multiplexer grounds the selected FSR terminal to enable current to flow through it. This developsa voltage at the output of the row amplifier which is proportional to the current variation in FSR.This in turn proportional to the applied pressure on the sensor. The row multiplexer selects the row, which routes the selected row amplifier output to the ADC. In fact we could scan the 100 channels with just one non-inverting Op-Amp instead of an array Op-Amps. But cross talk issues between sensor channels made this not workable. This core unit is switched in selectively by the control signals from the MCU which are driven by the firmware. These control signals switches the analog multiplexers available at the inputs and outputs of the Op-Amp array to select the element {row0, col0} and so on up to {row9, col9}. Once selected the resistance variation of the at particular FSR element can be captured as the voltage variation at the input of the ADC.

1.4. Miniature Data Acquisition Module

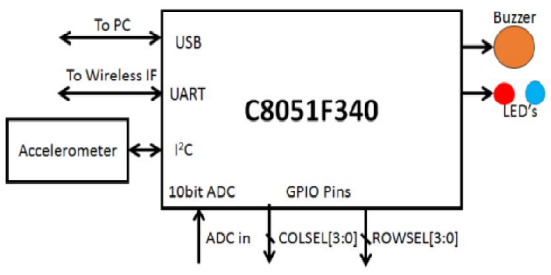


Fig.8. Miniature Data Acquisition Module

Block diagram of this Miniature Data Acquisition module is as shown in Fig.8. This module designed based on Silicon lab's 8051based MCU C8051F340 which contains peripherals such as ADC, USB, SPI, and UART and so on and can run at 48MHz [11]. The amble processing power available and its low power modes makes it possible to design a light weight wearable pressure measurement system with low power consumption. The on chip ADC is 10bit resolution with up to 200ksps sample rate and would fit nicely for the pressure measurement purposes.

In this design MCU periodically wakes up and scans the 100 pressure channels by setting appropriate values in COL [3:0] and ROW [3:0] pins to select the particular pressure sensor. Once the sensor is selected ADC conversion is enabled in MCU which converts the analog pressure value into 10bit digital value.

Digital values of the 100 channel pressure data is stored in an array in its internal memory after applying the calibration data as per the quadratic equation shown in Fig.3.of the curve fitting graph. The pressure threshold values can be set to activate buzzer or blink LED's to indicate the user that he is exceeding normal pressure values. There is also an on board accelerometer which can measure and predict the activity of the person wearing the foot pressure measurement system and can be used in conjunction with the pressure values to predict risk level of the pressure alarm. Optionally this data can be off loaded to a remote server using an add-on Wi-Fi/Cellular module.

1.5. Power Management Module

Any portable/wearable system should be fitted with rechargeable battery with necessary charge management circuits as well as the DC-DC conversion circuits to power various circuit blocks. The power management module is as shown in Fig.9.

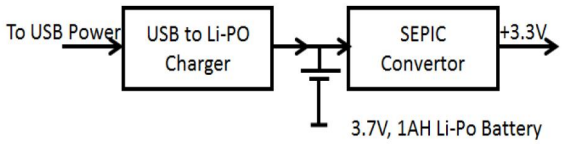


Fig.9. Power Management Module

USB to Li-Po Charger is a single Chip Li-Po charge management chip MCP73833 from Microchip which handles the charge management of the 3.7V, 1AH Li-Po battery in this design [12]. The SEPIC convertor Chip LT1308 from Analog Devices is used to generate 3.3V DC from varying 2.7V-4.2V Li-Po battery voltage [13].

III. RESULTS

The dynamic foot pressure measurement system is tried out with volunteers. The typical results obtained is as shown in the following Fig.10 and Fig.11. The legend r0c0 means the sensor value at ROW0 &COLUMN0.

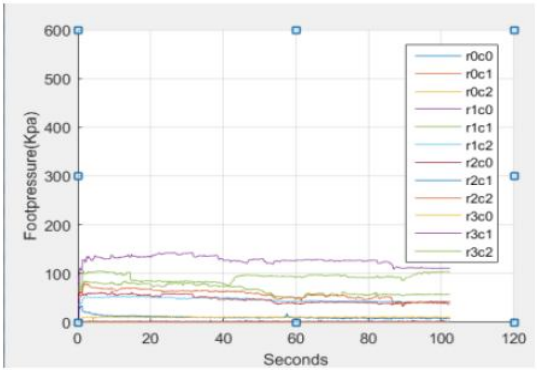


Fig.10. Pressure Measurement – Standing

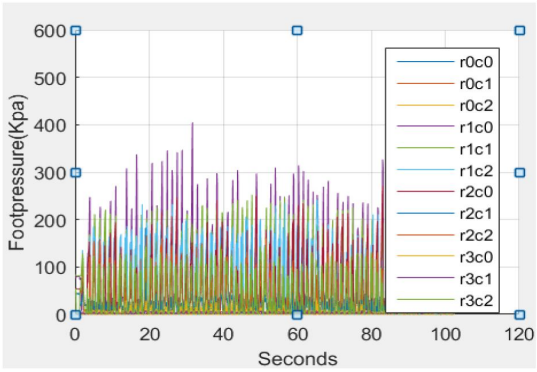


Fig.11. Pressure Measurement – Walking

The standing pressure data shows no periodic activity and the pressure levels on all the sensor positions is less than 150Kpa while the walking data shows the periodic activity and can max out to 300Kpa. The pressure values can be monitored for any abnormal/sudden increase to activate an alarm.

CONCLUSIONS

Dynamic Foot Pressure Measurement System has been designed and developed. Up to 12 channels of pressure measurement has been performed and the results are presented. From this we can conclude that this system is indeed can be used to measure the pressure data on the diabetic neuropathy patients and warn them of the risky pressure levels during their daily activity.

Hence, this system will help them avoid occurrence of the DFUs and keep them in good health and hopefully increase their life span.

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REFERENCES

[1] Reiber GE, Lipsky BA, Gibbons GW.," The burden of diabetic foot ulcers", Am J Surg 1998; 176:5S-10S.

[2] Harrington C, Zagari MJ, Corea J, Klitenic J.,"A cost analysis of diabetic lower-extremity ulcers", Diabetes Care 2000; 23:1333-8.

[3] International Diabetes Federation IDF World Atlas 6th Edition

[4] Singh N, Armstrong DG, Lipsky BA.," Preventing foot ulcers in patients with diabetes', JAMA. 2005; 293:217–28

[5] Boulton AJ.," The diabetic foot: epidemiology, risk factors and the status of care", Diabetes Voice 2005; 50:5-7

[6] Van Schie CH.,"Neuropathy: mobility and quality of life", Diabetes Metab Res Rev. 2008; 24:S45–51.

[7] Owings TM, Woerner JL, Frampton JD, Cavanagh PR, Botek G. "Custom therapeutic insoles based on both foot shape and plantar pressure measurement provide enhanced pressure relief.", Diabetes Care 2008; 31: 839–844

[8] Waaijman R, de HM, Ar ts ML, et al.,"Risk factors for plantar foot ulcer recurrence in neuropathic diabetic patients." Diabetes Care 2014; 37: 1697–705

[9] Bus SA, Haspels R, Busch-Westbroek TE. "Evaluation and optimization of therapeutic footwear for neuropathic diabetic foot patients using in-shoe plantar pressure analysis." Diabetes Care 2011; 34: 1595–1600.

[10] "FSR4000 Series Data Sheet",Interlink Electronics, P/N: PDS-10004-C.

[11] "C8051F340/1/2/3/4/5/6/7/8/9/A/B/C/DFull Speed USB Flash MCU Family Data Sheet," Silicon Labs. Rev. 1.4 – Sept. 2009.

[12] "MCP73833/4: Stand-Alone Linear Li-Ion / Li-Polymer Charge Management Controller data sheet," Microchip Corporation. DS22005A - 2006.

[13] "LT1308: Singel Cell High Current Micropower 600KHz Boost DC/DC Convertordata sheet," Linear Technology Corporation. 1308i LT/TP 0198 4K–Jan.1998.

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