RESEARCH PAPER

Plantar Pressure Data Acquisition System Using Velostat

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Abstract**—**In the present study, we discuss the design, manufacture and testing of a novel, flexible and wearable pressure sensor based on peizo-resistive effect of velostat. Subsequently, a wireless data acquisition system is developed to acquire data in real-time. The proposed system is ideal for clinical gait analysis and footwear evaluation due to its dynamic range, non-invasive nature and flexibility.

Keywords—Plantar Pressure, Wearable Sensors, Velostat, Wireless System, Data Acquisition System, Gait analysis.

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I. Introduction

Gait is an important indicator of health [20]. Analysis of gait can provide very useful insights for the diagnosis of many neurological disorders like Parkinson's Disease (PD) [20,24]. Gait analysis is extensively used in standard medical tests such as Unified Parkinson's Diseases Rating Scale (UPDRS) studying deterioration of motor skills among patients suffering from Parkinson's Disease [3]. Certain changes in gait often indicates underlying Bradykinesia which is an excellent indicator of neural degenaration associated with Parkinson's Disease [1].

Although there are a lot of standardized tests available for analyzing deterioration of gait, the common problem with these procedures is that they are purely qualitative in nature [24]. Diagnosis is limited by the expertise of the observer and errors in judgement. Thus, there is a growing need for quantitative analysis of gait.

Various methods have been proposed in the direction of quantitative analysis and measurement of gait parameters. Measuring and monitoring plantar pressure or feet pressure is an execellent option for gait analysis [4]. Flexible pressure sensors in combination with wireless data acquisition systems enable continuous monitoring of patients which is very advantageous in disease management, rehabilitation and therapy [9]. The objective is to design a data-efficient, effective and reliable plantar pressure monitoring system which is capable of collecting data over long durations of time.

The collected data can further be analyzed using statistical methods inorder to provide meaningful inferences for th diagnosis of various disorders like Parkinson's Disease and evaluating athletic performance in various sports [4].Related Works

Phillips et al [1] discussed the differences between general slow movement and bradykinesia in Parkinson's disease and have concluded that bradykinesia is infact a neccessary condition for Parkinson's disease and not a compensatory symptom. The researchers have also discussed the neurological causes and implications of bradykinesia.

Berardelli et al [2] discussed the causes of bradykinesia and it's pathological implications in Parkinson's disease. Thay have analysed EMG and EEG waveforms of patients suffering from Parkinson's disease and compared the results with normal waveforms.

Goetz et al [3] introduced a revised climetric testing program for evaluating motor skill deteroration among patients suffering from Parkinson's disease called MDS-UPDRS improving upon pre-existing evaluation formats. Various cognitive and motor skills have been subject to evaluation based on a scale.

Razak et al [4] have reviewed the various biomedical applications of plantar pressure sensors. They have discussed various sensors and systems available for plantar pressure sensing. Recent trends, adoption of IoT and wireless systems have also been discussed in detail.

Light et al [5] designed a fall monitoring system based on based on 6x21 insole pressure sensor array. The generated data is transmitted to a computer using a bluetooth module for further analysis. Unrefined data consists pressure data for different types of falls. The sensor matrix is divided into three grids – toe grid, arch grid and heel grid. Various algorithms have been evaluated for predictive modelling.

Gerlach et al [6] introduced a gait analysis system based on peizo-resistive MWCNT sensors for prevention of diabetic ulcers among users. Six single CNT pressure sensors interfaced with the help of multiplexers. The pressure data obtained was analyzed to detect patients with high risk of feet ulcers.

Schlachetzki et al [7] introduced a novel system for measuring various gait parameters such as stride length, swing phase, gait velocity etc., using wearable tri-axial accelerometer and gyroscope. Postural instability and and longitudinal assessment of gait was also considered. Data

streamed with the help of bluetooth with sampling rate of
51.2 Hz.

Munoz-Organero et al [8] designed a system for offering better walking strategies for patients suffering from osteo- arthritis an array of eight FSR sensors embedded to the sole of the shoe. The sensors were interfaced to M420 microprcessors with the help of multiplexers and a signal conditioning system. 8-bit data witha sampling rate of 100Hz was transmitted with the help of a blueooth module. Pressure patterns were analyzed using mahalanobis distance.

Malvade et al [9] designed an IoT-based data acquistion system for plantar pressure sensors. An array of five FSR sensors was used. The data generated by the sensors was transmitted to a mobile device using bluetooth. The data received by the mobile device was again transmitted to an API server for further analysis.

Suprapto et al [10] have presented a low-cost 32x32 velostat pressure sensor matrix for feet pressure distribution measurements. Each sensor is accompanied with a reference resistor to form a voltage divider configuration. Current barrier circuit has also been included to prevent cross-talk between the sensors due to leakage current. The obtained output signal is interfaced with the help of a 10-bit Analog- to-Digital converter (ADC).

Lou et al [11] proposed a flexible pressure sensor based on peizo-resistive properties of graphene films placed on a polyester material. This sensor has high range and good response characteristics. A dynamic wireless plantar pressure monitoring system has been designed around these sensors for clinical gait analysis.

Vilarinho et al [12] designed an optical fiber based on fiber bragg gratings to measure plantar pressure. A strategically placed array of five FBG were used for acquiring data. The sensors were interfaced with the help of optical interrogator devices.

Rajala et al [13] designed a plantar pressure measurement system using peizo-electric polymer film sensors. Eight points were considered considered for measurement. The obtained signals were analyzed with respect to body mass, age and height among five test subjects.

Aich et al [14] designed a gait analysis system for detecting shuffling gait using 3-D motion captures (camera- based). RBF kernel along with MRMR feature sets has been used to train the predictive model. Accuracy of 98.54% has been obtained.

Deng et al [15] proposed a self-powered plantar pressure mapping system using peizo-electric nanogenrators (PENG). A data acquisition system has been developed using an array of eight PENG sensors. The sensors are interfaced using charge amplifiers, Analog-to-Digital converters and a bluetooth module for communication.

Hopkins et al [16] proposed an in-socket pressure monitoring system for prosthetic limbs using peizo-resistive velostat pressure sensors. The sensors are combined with a pull-down resistor to form a volatage divider configuration. The sensors are interfaced with the help of multiplexer in combination with diodes to prevent cross-talk. Intertial measurement unit (IMU) and bluetooth module has been used for data acquisition and transfer.

Zhang et al [17] designed fabric based flexible sensors based on silver electrodes and a cotton cloth di-electric medium. A series of three sensors were used to collect data.The sensors were interfaced with the help of a capacitance measurement embedded chip. The obtained signals were used for gait analysis.

Zhao et al [18] designed a flexible matrix based wearable plantar sensor for gait analysis. The sensor uses a nano force sensitive semi-conductive ink sandwiched between two electrodes. The ink acts as a peizo-resistive material. An array of sixteen sensors were used for sensing. Data acquisiton system based on 12-bit ADC, multiplexers and STM32 MCU. Bluetooth module used for data communication.

Momin et al [19] proposed a system to classify human activity such as walking, jumping and running. The system is designed around carbon nanotube material coated into cotton fibers sandwiched between nickel electrodes. An array of three sensors are used to collect data. Center of gravity also considered for analysis.

Pardeol et al [20] discussed early detection of freezing gait in patients suffering from Parkinson's Disease using inertial measurement unit (IMU) and plantar pressure distribution data. Methods for data collection, labelling and various other topics related to detection of freezing gait and scaling in accordance with UPDRS III were discussed.

Keatsamarn et al [21] designed an optical sensor based plantar pressure monitoring system for posture control and person identification. LED strips along with acrylic plates and digital camera board are used o obtain color-coded plantar pressure data. The obtained data is used to train a CNN model for biometric applications.

Ciniglio et al [22] designed a 16-sensor plantar pressure monitoring layout for a wide range of applications from measuring athletic performance to clinical analysis. Pressure contours obtained can be used for analyzing a number of parameters.

Bucinskas et al [23] proposed a wearable plantar sensor for fall detection and gait diagnosis. Wearable sensor based on peizo-resistive velostat material sandwiched between two aluminium elecctrodes laminated with PVC film on both sides was used for sensing plantar pressure. An array of three such sensors was interfaced with the help of a ESP32 micocontroller. The transmitted data was stored in a MS Excel database.

Lu et al [24] have discussed the problems associated with UPDRS assessments and ambiguity involved with it's qualitative nature and proposed a quantitative assessment based on computer vision and machine learning. The test scores obained indicate the severity of motor neuron degeneration.

II. Sensor design

Velostat (also known as linqstat) is a flexible, low-cost, peizo-resistive material. It is ideal for making flexible pressure and flex sensors which can be easily incorporated into footwear design. The use of peizo-resistive material also provides excellent immunity to noise compared to other materials [9].

In order to obtain optimum results, five pressure points were identified on the foot. The sensors are strategically placed on these pressure points in order to measure change in pressure during each cycle of gait.

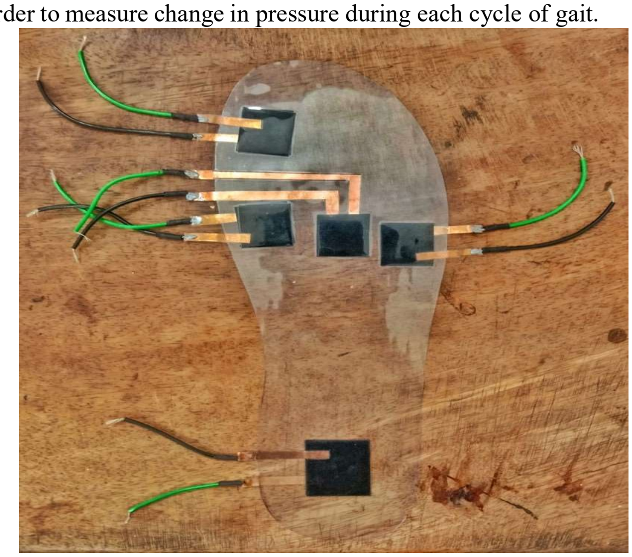

Fig. 1. Velostat material used for sensor design.

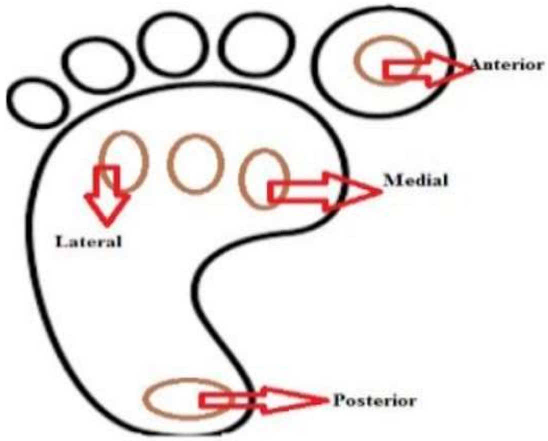

Fig. 3. Fabricated insole sensor array.

III. Interfacing Circuit and Data Acquisition

The sensors under consideration are peizo-resistive in nature. Which means the resistance of material changes proportionally with change in pressure. In case of velostat, resistance of the material decreases with increase in pressure.

Using the principles of impedance spectroscopy, the change in resistance of the material can be detected by applying a constant voltage across the electrodes and measuring change in current with respect to change in resistance.

This analog signal in form of current can be used to measure change in pressure. Since current and resistance are inversely proportional to each other, magnitude of current increases with increase in pressure.

Using Ohm's law,

$$V = I \cdot R \quad (1)$$

where,

Fig. 2. Pressure points identified [9].

The peizo-resistive material is cut into squares of dimensions 20mm x 20mm. In order to integrate the material with the interface electronics, two electrical leads made of flexible copper strips are provided to each sensor.

The entire setup is then fabricated using 5mil thermal laminate sheets in order to provide ample flexiblity and minimize air gaps during the thermal lamination process.

The laminated sheet is then shaped according to the footwear design. The designed sensors are then subject to impedence spectroscopy tests in order to gauge important parameters like range, sensitivity and response in laboratory conditions.

The designed sensor array can further interfaced with an appropriate signal conditioning circuit in order to measure change in plantar pressure accurately with help of a microcontroller unit. V = Applied voltage (V_{cc}).

I = Current.

R = Resistance of the sensor (Pressure depedent).

Using (1) we get,

$$\Delta I = V \,/\, \Delta R \quad (2)$$

where,

ΔII = Change in current.

ΔIR = Change in resistance.

The sensor outputs are coupled with IN-4007 diodes in order to prevent cross-talk [10]. The analog outputs of the sensor are of low magnitude and have to be conditioned in order to interface them with the MCU. We also have to consider the array contains multiple sensors which have to be interfaced at the same time. Thus, in order read multiple channels simultaneously, suitable multiplexers have to be used. The output of the multiplexer is then amplified according to the requirements using a programmable gain amplifier. The amplified analog signals are then fed into a

16-bit Analog-to-Digital converter (ADC). The obtained digital values are communicated to the MCU using I2C communication bus.

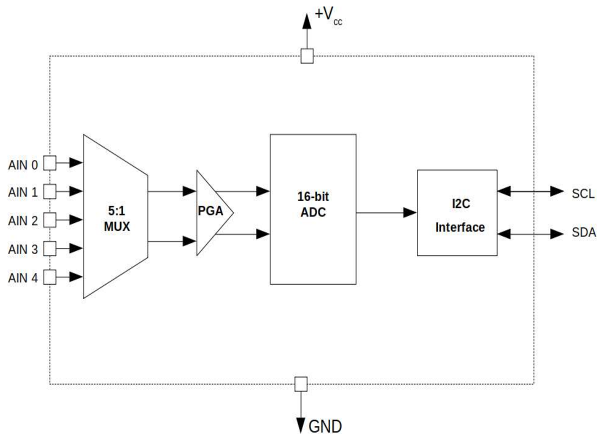

Fig. 4. Functional block diagram of the interfacing circuit.

The I2C protocol uses master-slave configuration for communicating data. The MCU acts as the master and controls communication between the signal conditioning block.

RP-2040 microcontroller board (Raspberry Pi Pico) is used for this purpose. RP-2040 is a powerful 32-bit ARM Cortex M0+ processor with dual-core capabilities. It's compact design, low power comsumption, high clock frequency of upto 133MHz and 2MB flash storage makes it ideal for implementation in wearable devices.

The interfaced pressure readings are then communicated to a computer using a Bluetooth module. The obtained data can further be analyzed on the computer to gain useful insights on gait and can be used for a wide range of applications.

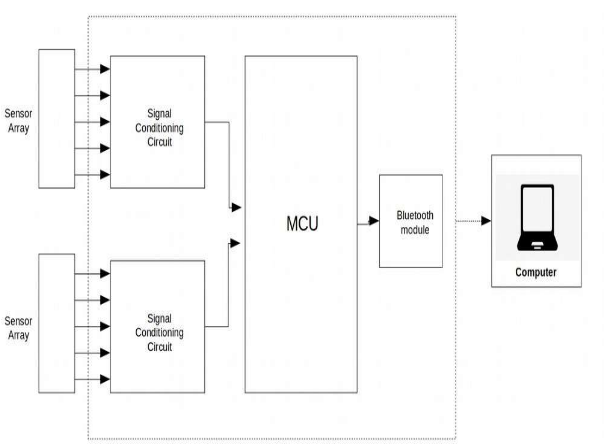

Fig. 5. Overview of the system.

IV. Results and discussion

The objective of sensor design is to optimize sensor characteristics in terms of range and sensitivity. The response of the sensor must ideally be linear with respect to applied stimulus that is pressure. In other words, the output of the sensor must vary linearly with respect to applied pressure.

In order to further improve the design of the sensor, we investigate the effect of thickness of the velostat material on sensor response. To study this phenomenon, we consider four different layouts. We increase the thickness of the material by progressively stacking layers of velostat material upon each other. The first layout contains a single layer of velostat laminated with a 5mil thermal lamination process. The second layout contains two layers of velostat material stacked upon each other and so on. Thus, a total of four sensors were obtained for testing. Based on the performance, the ideal candidate is selected for deployment.

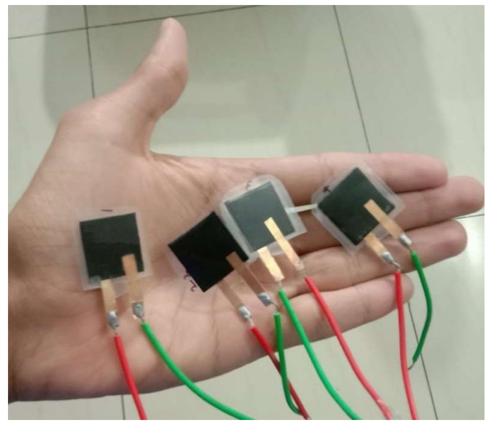

Fig. 6. Sensors considered for testing

Three point calibration technique was used for analyzing sensor characteristics. The sensor output was measured for three weights - 20kg, 40kg and 60 kg.

The weight in kg is converted to absolute pressure using formula,

$$P=W / A \tag{3}$$

where,

W = weight (in newtons)

A = Area of the sensor surface (2cm * 2cm)

Using principles of impedance spectroscopy, a biasing voltage of 3.3V was applied across the sensor. The change in resistance of the sensor was measured as change in current. This change in current was measured with the help of an ammeter connected in series with the sensors.

The amplitude of output current was tabulated and represented graphically to analyze sensor characteristics.

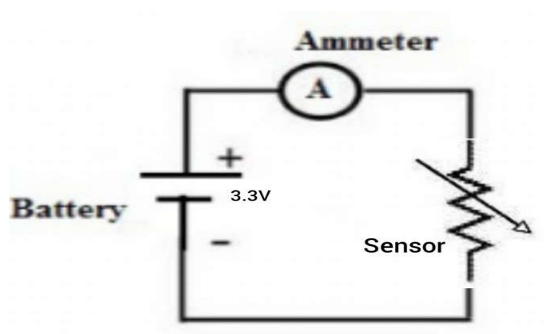

Fig. 7. Schematic representation of testing circuit.

The results obtained are graphically represented as below. The output characteristics of the sensor is plotted in terms of output current v/s applied pressure graph for various values of thickness (N=1,2,3,4). Using this data, the sensitivity and range of the sensor can be determined.

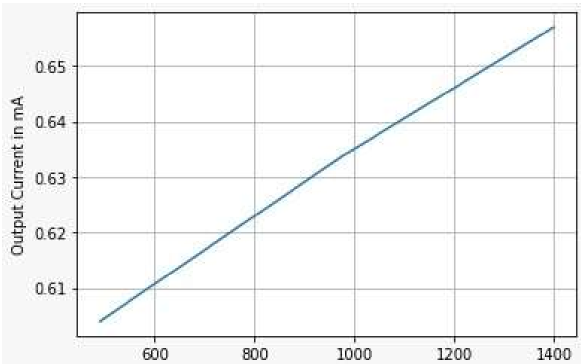

Fig. 8. Output Characteristics for N=1.

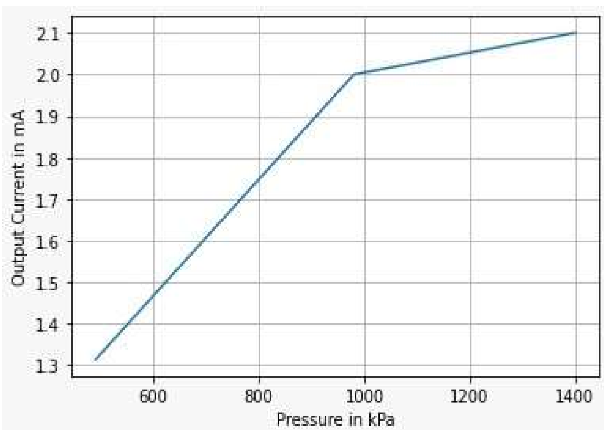

Fig. 9. Output Characteristics for N=2.

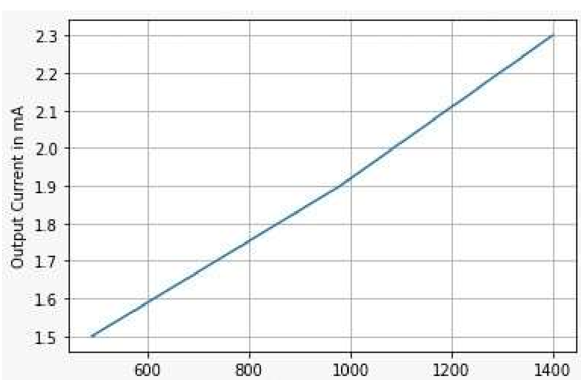

Fig. 10. Output Characteristics for N=3.

It is observed that for N=1, even though the response of the sensor is linear, the sensor has very limited range and sensitivity. This is not preferred for interfacing. For N =2, the sensor has excellent sensitivity but attains saturation very quickly around applied pressure of 1000kPa. Further increase in pressure results in minimal increase in output current.

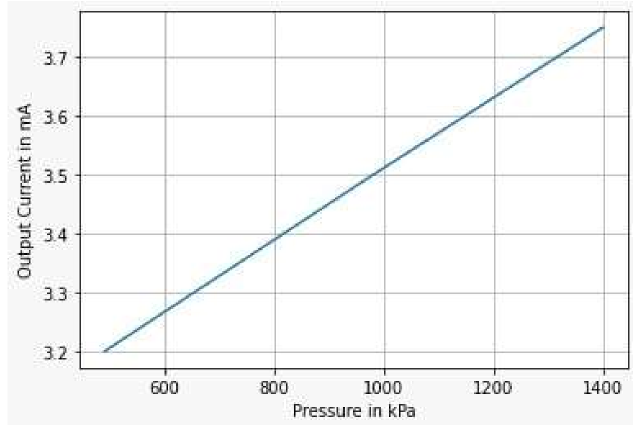

Fig. 11. Output Characteristics for N=4.

For N=3 and N=4, The sensors have optimum range and sensitivity. Generally, the response of the sensor is linear and are ideal candidates for deployment. N=4 is more preferred due to increased amplitude of output current and perfectly linear characteristics which is excellent for interfacing. Thus, N=4 appears to be ideal for implementation in the data acquisition system.

V. Conclusion

In the present study, we have designed the sensors and also discussed the development of a plantar pressure data acquisition system using piezo-resistive velostat sensors. We have also discussed the effective thickness of velostat and recorded the characteristics of them and found the ideal characteristics among them. The advantages of the system are cost-effectiveness, dynamic range and scalability. Furthermore, the flexible, non-invasive nature of the sensors make it an ideal choice for implementation in clinical gait analysis.

VI. Scope for Future Work

1. Sensor data can be used for clinimetric gait analysis.
2. A System-on-Chip(SoC) can be developed for increased integration with footwear design.
3. Wearable sensor network can be developed to increase scalability of the system and for large scale implementation.
4. Further tests to be performed for better analysis of sensor characteristics.

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