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Design and development of ShrewdShoe, a smart pressure sensitive wearable platform

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ABSTRACT

This study introduces a wearable in-shoe system for real-time monitoring and measurement of the plantar pressure distribution of the foot using eleven sensing elements. The sensing elements utilized in ShrewdShoe have been designed in an innovative way, they are based on a barometric pressure sensor covered with a silicon coating. The presented sensing element has great linearity up to 300 N and is very durable. It can withstand excessive burst pressures without any damage. This makes ShrewdShoe applicable in a variety of fields such as gait analysis, activity analysis, sports performance optimization, and detection of gait disorders. ShrewdShoe comes with a built-in IoT (Internet of things) module in order to wirelessly communicate with a PC or smartphone. Due to its low cost and durability, it can be used for everyday wear in order to continuously acquire data. Plantar pressure distribution of the foot maps has been constructed based on obtained data and used for preliminary validation of sensor readings.

1. Introduction

Walking is one of the most basic forms of activity, however, with observing and analyzing one's walking pattern many health-related details will be revealed. Utilization of in-shoe plantar pressure sensors is a proper method for gait analysis [1]. This can assist patients with gait disorders as well as healthy people to overcome or prevent unhealthy walking habits.

This study introduces ShrewdShoe, a smart shoe with built-in pressure sensors for everyday use. Pressure sensors and all relative circuitry are well hidden behind the insole of the shoe making it feel almost like a normal shoe. All the necessary electrical components are built in inside the shoe and user requires to wear no additional attachments in his/her waist or chest. ShrewdShoe is a standalone wireless-enabled wearable platform for measuring plantar pressure distribution in the foot. It consists of modular sensorization of the insole with eleven pressure sensors integrated with a battery and an Internet of things (IoT) module forming an independent platform that can transmit all the sensor data and analysis to a PC or smartphone in real-time. It can typically last 5 hours continuously working when deployed. The presented in-shoe system can calculate the center of pressure (COP) across the plantar surface of the foot in real-time. This assessment can help form a comprehensive gait characteristic for a person, gait characteristics can have significant value in a variety of applications. These applications are discussed later in detail.

The most important part of developing ShrewdShoe was designing a suitable sensing element. It should feel natural against the human skin and therefore should be soft and have a certain degree of elasticity. Recent advances in the field of human-robot interaction (HRI) propose a simple method to build such a sensing element. It has to have a flexible layer on top of the actual pressure sensor in order to feel like a soft and skin-like sensing element. This mechanism would work

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in such a way, the flexible layers would compress and deform to an extent, and this deformation would then transfer the applied forces to the integrated sensing element. One study has successfully implemented this method to create a tactile sensor. MEMS barometric pressure sensors have been integrated with a foam rubber coating, the foam rubber would act as a soft mediator that would transfer forces to the barometric sensor [2].

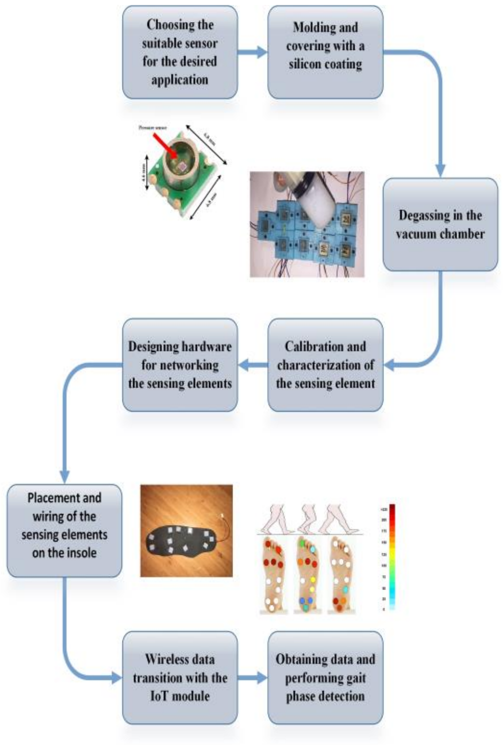

Fig. 1. This flowchart briefly demonstrates the design and development procedure of ShrewdShoe.

2. Related Works

There are two common methods for measuring plantar pressure distribution of the foot, stationary force platforms vs portable in-shoe systems. Despite the decent accuracy and clinical importance of stationary systems such as Novel [3] and Zebris Medical GmbH [4]. These platforms have many drawbacks. Stationary force platforms work great for bare-foot walking analysis, but they cannot be used where reaction forces of the insole of the shoe with the foot itself need to be measured. However, the main limitation of the stationary platforms is the lack of portability. They can only be used in clinical environments and gait analysis can only be done for flat and even surfaces while walking straight.

Due to the above limitations of the stationary force platforms and the clinical demand for measuring plantar force distribution, developing in-shoe systems with extreme portability that can be used for everyday wear has become a trending topic in the recent years.

In the field of wearable technology some commercial products are available, e.g. F-scan (Tekscan, Boston, MA, USA) uses FSR [5], the Pedar (Novel, Munich, Germany) uses capacitive sensors [6], and the ParoTec (Paromed, Neubeuern, Germany) which uses piezo-resistive sensors [7]. All three require additional wiring attachments at the ankle or hips limiting their portability and therefore practicality. It should also be mentioned that they are very expensive.

Recently researchers have produced more portable in-shoe systems such as [8-10]. These three systems do not have sufficient resolution and sensitivity to form a precise pressure map that can be used for clinically valuable gait analysis. Another more recent in-shoe system is [11] which has 64 sensing elements, but one major drawback is the sensing elements are not well accustomed to everyday activity on uneven surfaces because they would be damaged at a burst pressure of 100 N/cm2 or higher [1].

ShrewdShoe is the least expensive option among currently available prototypes. It has a decent sensor resolution with a very high maximum pressure and burst pressure range, mentioned with more detail in the later sections.

3. Deployable Applications

Each person has an individual walking pattern which depends on many factors [12] e.g. hip, knee, and foot pathology, neuromuscular and nervous system, sensory functions, postural reflexes, age, walking speed, etc.

The main application of measuring the plantar pressure distribution of the foot is for gait analysis. Gait is initiated with hip and knee flexion, after a short phase of leg swing which is made possible by shifting all the weight to the other foot, the heel of the foot is placed on the ground. After leg swing, the heel starts bearing some weight and the weight gradually shifts forwards so the other foot could execute the same cycle [12].

Performing gait analysis opens the door for ShrewdShoe to be deployed in a vast variety of applications listed below.

3.1. Gait phase detection

Every individual’s walking pattern forms from a continuous series of sequences. In general, gait can be divided into four phases [10].

- Force production phase that will lead to lifting the foot from the ground. It is done by shifting the weight to the ball of the foot and lifting the heel of the ground.

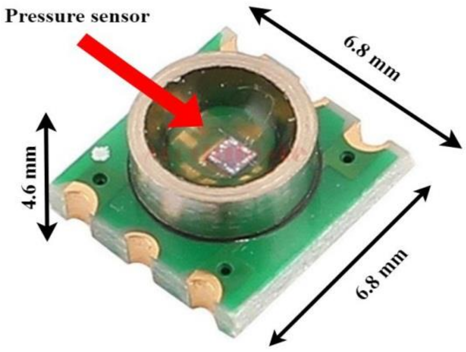

Fig. 2. Overview of MD-PS002, the barometric Pressure Sensor used in the sensing elements.

- Swing phase is where no pressure is being applied to the ground from the foot and foot is swinging in mid-air.
- Ground contact phase is when the foot first contacts the ground, which is usually through the heel.
- One leg stance phase where the whole body weight is supported by one leg so the other leg can swing in the air.

Data extracted from ShrewdShoe can be used for gait phase detection.

3.2. Activity Analysis

The proposed in-shoe system can easily be expanded to detect all sorts of daily activity such as walking, sitting, standing and going up and down the stairs. Constant measurement of daily life activity can be used for healthcare applications. This data can be used for assessment of healthy people and preventing long-term impairments.

3.3. Sports Performance Optimization

Thanks to the high linear range of the pressure sensing elements used in this study and the fact that they can withstand a great range of force and remain intact, ShrewdShoe can be utilized in intensive sports consisting sprinting and jumping. Individual exercise patterns can be obtained for athletes so they can use the extracted data to perform at higher levels. Extracted data can also be used in minimizing the risk of injuries and in the field of sports medicine.

3.4. Gait disorders

ShrewdShoe can be used for identifying some types of gait disorders and abnormalities such as foot drop compensation in gait cycles, hemiplegic gait, diplegic gait, and ataxic gait [12].

Classification of gait disorders is the first step for any therapeutic intervention and can speed up the treatment process, especially in senior citizens where gait disorders are indicators of more serious health problems in the future [13, 14].

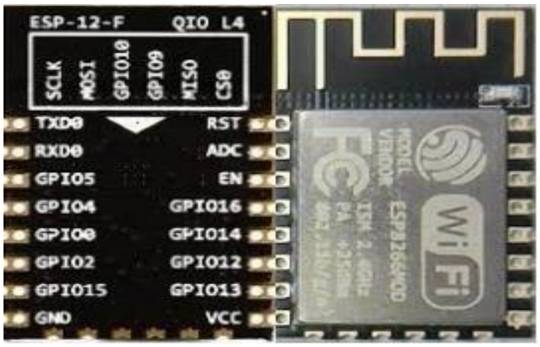

Fig. 3. ESP12 series overview, SoC chip, pin-out, and PCB antenna are visible.

3.5. Flat foot

In normal gait, arch of the foot would not contact the ground very much nor bear much weight. We have placed a pressure sensor in the insole specifically in the arch of the foot where it normally would not sense any pressure. A case of the fallen arch can easily be diagnosed while using ShrewdShoe, therefore, therapeutic interventions could take place [15].

3.6. Diabetic foot

Diabetic patients often show some form of gait abnormality and their walking pattern differ from healthy people, i.e. improper foot plantar pressure distribution when compared to non-diabetic people. There are some distinct gait patterns seen in diabetic patients such as longer stance phase [16].

Diabetic foot ulcers can lead to serious problems such as septic infection, septicemia, and lower limb amputation. To prevent these from happening, data gathered from ShrewdShoe can help utilize pressure offloading method. This method has been proven to effectively treat plantar foot ulcers. Decreasing the pressure on some key pressure points of the foot can help avoid the recurrence of ulcers [17].

3.7. Other Applications

- Fall detection and taking appropriate actions [18]
- Detecting imbalances for fall prevention

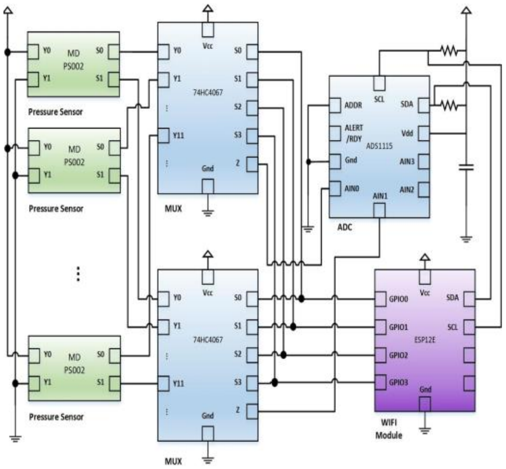

Fig. 4. Hardware schematic, consisting of an IoT module, an ADC module, two 16-to-1 multiplexers, and eleven sensors.

- Detecting the slope of the walking path
- Detecting the terrain type, e.g. dirt, grass, pavement, and other uneven surfaces.
- Footwear design and evaluation [19]

4. Design and Development

4.1. Hardware Description

Fig. 1. Demonstrates the design and development procedure of ShrewdShoe. All the electronic components used in ShrewdShoe are listed below.

4.1.1. Pressure Sensor

The most important decision in the development process was choosing the right pressure sensor for integration on the insoles. A large variety of pressure sensors are available and can be used to form the desired sensing element, including MEMS-based capacitive sensors, force sensitive resistors (FSR), piezoelectric [20], magnetic [21], and optical sensors [22]. A lot of factors need to be considered for choosing the best sensor for our purpose, e.g. form factor, cost, power consumption, reliability, sensitivity, range of linear response, absolute range, operating temperature, etc. Our first choice was a MEMS barometric pressure sensor called MPL115A2 Freescale Semiconductor. This barometric pressure sensor consists of a silicone diaphragm transferring forces to a Wheatstone bridge to measure the pressure of the air passing through the diaphragm. After packaging this sensor with different kind of silicone coatings in terms of thickness, hardness, and etc., we decided that it was not up for the task. The main problem was that the linear range of the sensor was originally too small i.e. 4 N, and could not be extended significantly even after injecting a thick silicon layer on top of it. This would essentially conflict with our design and selected sensing resolution. In addition, MPL115A2 did not prove to be resilient enough to be used in a harsh condition like a shoe, as burst pressures applied momentarily during different kind of activities would cause permanent damage to the sensor.

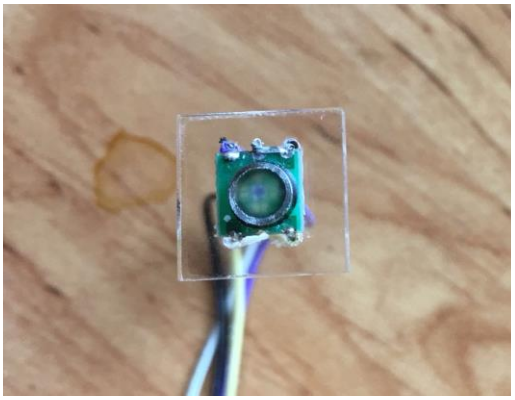

Fig. 5. Barometric sensor mounted on a plexiglass base.

Our final choice is the tiny (6.8mm × 6.8mm × 4.6mm) yet very resilient and durable MD-PS002 barometer which suits every aspect of the original design idea we had in mind (Fig. 2). This low-cost, low power sensor is designed to work in tough environmental conditions making it ideal for integration inside a shoe. It can measure a pressure range of 150 kPa with a linear accuracy of 0.25% FS.

4.1.2. IoT Module

In order to read sensor values, process data and wirelessly communicate with a PC or a hand-held device, An IoT module is placed at the heart of this design.

ESP12E is a low-cost SoC with a very small form factor (24 mm × 16 mm × 3 mm). It has a 32 bit MCU with 80 MHz clock frequency, 2.4 GHz WiFi module with 3DBi onboard PCB antenna, 4MB integrated SPI flash, a 10-bit ADC, 11 GPIO pins and an operating temperature range of 40C - 125C. It is a power efficient module with an average power consumption of 150mA and 15mA-100uA in sleep modes.

The ESP WiFi module can work as a WiFi station and connect to already existing WiFi networks. It can also operate as a soft access point to create an independent WiFi network. Finally, ESP can work in station and access point mode simultaneously. In this study, we utilize the ESP module in soft access point mode (Fig. 3).

In order to form a practical development system ESP requires a TTL to USB serial adapter and a voltage regulator and from there we can proceed to program the module.

Programming the ESP can be done in various ways, e.g. basic AT commands, Arduino IDE, and Lua based firmware.

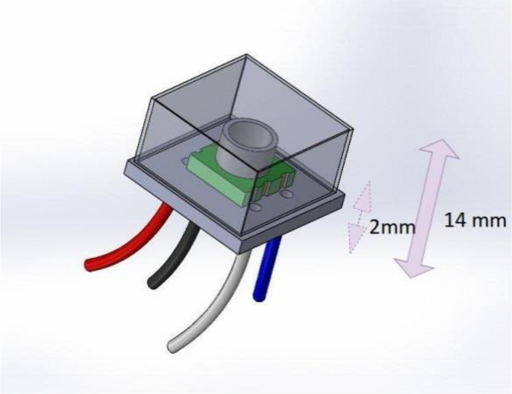

Fig. 6. A 3D model showing the design of the sensing element used in ShrewdShoe.

In this study, we have used the latter method based on Lua programming language, an asynchronous and event-driven way to read sensor data via I2C, process data and transmit the data to a local HTML server, accessible from a PC or any wireless-enabled hand-held device connected to the access point created by ESP.

In order to take advantage of the Lua programming language, we had to build our own custom firmware with only some selected software modules to minimize the flash storage usage. After flashing the firmware to the chip using the open source flasher software we could easily upload the Lua code to the chip using a free open source software called ESPlorer, developed in Java. It should be noted there are other ways available for flashing the chip and uploading the code.

4.1.3. Other Components

Some additional components are used in order to monitor all pressure sensors in real-time. Fig. 4. Shows the schematic design of how ESP module communicates with the sensors. The barometric sensor output consists of two differential analog values henceforth two 16-to-1 analog multiplexers (74HC4067) are used in parallel to deliver the desired sensor value to the ESP module.

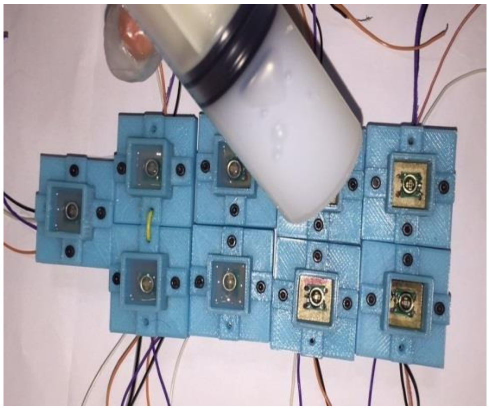

Fig. 7. Injection of RTV silicon into the molds.

The sensor selection is done by the ESP via four GPIO select lines connected simultaneously to both multiplexers. Since ESP only have one analog pin, a discrete analog to digital converter (ADC) module (ADS1115) is used as an interface for conveying the differential analog values to the ESP module via I2C protocol. The ADC module has a resolution of 16 bits, so there will not be any significant loss of sensitivity in sensor readings. All the electronic components are powered a 3.7 volt one cell Li-ion battery pack with a capacity of 1050mAh. The battery had to be reasonably small so a battery with the dimensions of 36mm × 42mm × 0.6mm was chosen.

Fig. 8. The vacuum chamber used for degassing the silicon.

4.2. Sensor Packaging Procedure

In order to properly mount the sensors on the insole, we designed a unique package. A laser cut plexiglass with the dimensions of (1.4 mm × 1.4 mm × 2.0 mm) is used at the base with four wires coming out of the bottom (Fig. 5.)

This package should be able to withstand a great deal of pressure applied in every direction when deployed in the possibly hot and humid environment of the shoe.

The sensor mounted on the plexiglass will, therefore, get fully covered with a silicon layer in order to extend the barometric sensor capabilities for our desired task. The silicon coating has great benefits, it can protect the sensor against directly applied pressures. It can also immensely extend the pressure sensing range without any noticeable sensitivity loss. Silicon coating should securely stick to the plexiglass layer. For this purpose two pieces of 3D printed molds have been designed (Fig. 7.) so RTV Silicon with the hardness of 25 Shore A, could be injected to the mold. In order to increase the accuracy of the sensing elements and maximize the durability of the final package, the moldings have been placed in a vacuum chamber (Fig. 8.). Eventually, after a duration of six hours, the final sensing element is dried in room temperature and is ready to be used in the insole.

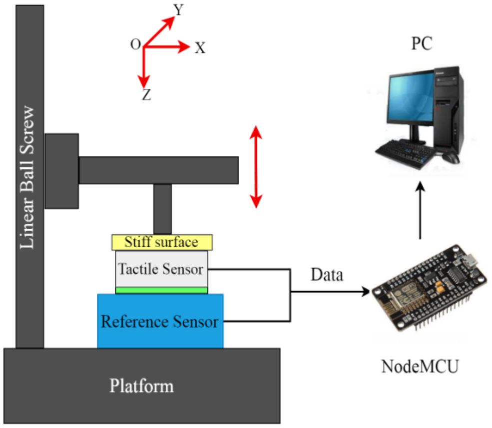

Fig. 9. Visual demonstration of the calibration platform

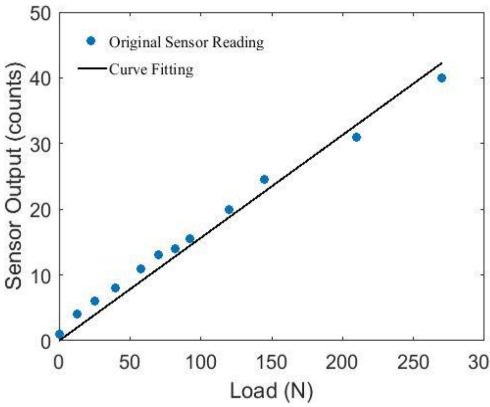

Fig. 10. This chart was plotted with MATLAB curve fitting tool for the data obtained from one of the sensing elements. This shows the promising linearity of our sensing element for ranges up to 300 N.

developed in order to find the exact characterization of each sensing element.

With this procedure, the barometric sensor is oriented to be safely placed in the bottom of user's feet, due to the fact that the final produced sensing element is flexible, thin, soft, and durable enough. Fig. 6. Shows the dimensions of the sensing element.

4.3. Calibration of the Sensing Elements

The array of sensing elements placed on the insole is, in fact, working entirely independent with minimal crosstalk. Therefore it is possible to calibrate each sensing element individually using an open loop method. A calibration platform was developed to simply read the sensor outputs while various forces were being applied. Gathering sensor data under different loads is crucial to determine the exact characterization of each sensing element. The calibration platform consists of a laboratory scale with the accuracy of ± 0.002 g, a ball screw with 0.01 mm linear displacement, and a microprocessor chip. Each sensing element would be mounted on the scale and with utilizing the ball screw it could be placed under different loads. Output data is sent wirelessly from the microprocessor chip i.e. NodeMCU to a PC for verification and processing. Fig. 9. Shows the mentioned calibration platform.

Our sensing element's linearity has been tested up to 300 N. It has great linearity in the tested pressure range with R-square > 0.99. Also, the designed sensing element package has been tested with a burst pressure of 1000 N in the lab without suffering any physical damage nor performance loss. Fig. 10. Shows the linear model for the analog readings of one of the sensing elements tested in the lab environment.

4.4. Insole Design

In order to keep design complexity and cost down, the total number of sensors are kept to a fair minimum. With an evaluation of all the previous plantar pressure distribution measurements, sensing elements are placed at only the most important anatomical pressure points [1]. It is worthy to note one sensor is placed at the arch of the foot and is mainly used to detect a fallen arch and similar gait abnormalities [15]. The fabricated insole was tested on various subjects with feet sizes of 42-43 EU to see how sensing elements contact the plantar surface of the feet and the accuracy of sensor placement has been validated.

The sensing element is glued on the insole while attached wires come out of small holes at the bottom, the required wires have been attached to a flexible flat cable which eventually comes out of the outside portion

Fig. 12. Final prototype of ShrewdShoe. Top picture shows the insole and connectors and in the bottom picture lateral attachment of the hardware case can be seen.

of the shoe to get connected to the main board. Fig. 11. Shows the insole with its required wiring attachments.

After fabricating the sensorized insole, it was placed at the bottom of the shoe while the required sockets get out from the outside portion of the shoe. All the electronic parts have been placed in a case and have been attached laterally onto the side of ShrewdShoe (Fig. 12). All the hardware attached to the shoe weighs less than 200 g and research suggests that hardware attachment of 300 g or less does not have a noticeable effect on gait [23].

5. Results

5.1. Plantar Pressure Distribution

Data obtained from ShrewdShoe was used for gait phase detection. Fig. 13. Shows the gait phases successfully detected from evaluating the data obtained by wearing the ShrewdShoe. Data was recorded for 15 steps of level walking while ShrewdShoe was worn by a male subject with 24 years of age, weighing approximately 70 kg.

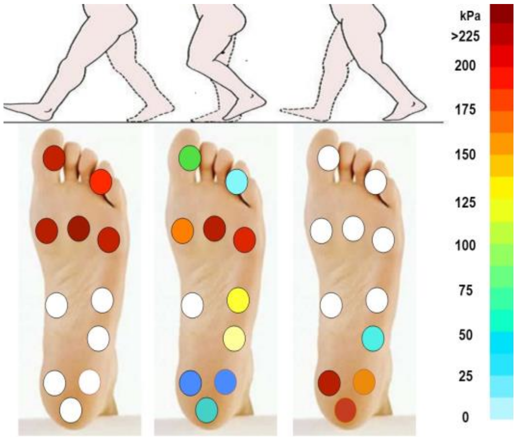

Fig. 13. Plantar foot pressure map of three gait phases, constructed from sensor readings. From left to right gait phases are 1) Force production/heel off 2) One leg balance 3) heel contacting the ground.

5.2. Estimation of the COP

We define the COP of the foot as the center of all applied pressures between the foot and insole of the shoe. When the number of sensing elements used in a design is relatively low, the well-known weighted-mean approach for estimating the COP might be more prone to errors, due to the fact that this method is not sensitive to the type and number of the sensors [24]. Recent research by [25] proposed an individual specific nonlinear model for estimation of the COP. This method is supposed to be more accurate than the conventional weighted-mean approach for estimating the COP.

In order to use the individual specific nonlinear model, an insole coordinate system had to be proposed to determine the exact location of each sensing element on the insole. Fig. 14. Shows the coordinate system representing the ShrewdShoe. As can be seen in Fig. 14. The X and Y axes are the tangent lines to the bottom and the left edges of the insole respectively. The intersection point of the borders was considered as the origin.

Table 1 shows the exact coordinate of each sensing element used in the ShrewdShoe. It should be noted coordinates have been measured with a digital caliper with the accuracy of ± 0.02 mm.

Table 1. Corresponding coordinates of the eleven sensing elements utilized in ShrewdShoe

Sensing Element Number	X coordinate	Y coordinate
1	17	264
2	61	253
3	8	195
4	40	199
5	70	191
6	15	111
7	65	115
8	61	88
9	12	39
10	56	44
11	34	29

In order to validate the correctness of the results, the final estimated COP trajectories were compared with references from similar studies that have been proven to be accurate [26].

6. Conclusion and Future Work

This study presented the design and development of ShrewdShoe. A wide range of applications have been discussed and it was shown that ShrewdShoe can be used in most intensive activities providing gait analysis in distinctive conditions that have great research value. The functionality of ShrewdShoe has been preliminarily validated through a demonstration of the plantar pressure distribution of the foot during three gait phases.

Future work consists of further evaluation of ShrewdShoe with multiple users, deploying it in sports medicine, and analyzing data when deployed in specific cases of gait disorder.

Several improvements can be done such as increasing the number of sensors which can easily be done without changing existing hardware, decreasing the height of the sensing element making it more concealed from users, and minimizing the weight of the additional hardware attached to the shoe.

Another significant modification to consider is using a flexible PCB in the next version of the ShrewdShoe. This upgrade will make the underlying system more modular, therefore, the hardware system may be easily adjusted and ported to be used in different shoe sizes. In addition, with the utilization of a flexible PCB, the durability of the integrated circuitry would be expanded.

Fig. 14. The corresponding sensor layout of the ShrewdShoe.

By applying some pattern recognition techniques, the software can be vastly expanded to include real-time gate phase detection. This can be used in the field of activity analysis and aid in the classification of gait disorders.

Also to take full advantage of ultra-low power consumption during the sleep mode of the ESP module, a dynamic method for decreasing power consumption can be developed based on online sensor readings which can greatly extend battery life.

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8. Biography

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Arsalan Amralizadeh obtained his bachelor's degree in electrical engineering from Tabriz University of Tabriz, Iran in 2017, respectively. He is currently a master's student in electrical engineering at the University of Tehran, Iran. He is also a member of the Human-Robot Interaction Laboratory (known as TaarLab for its Persian abbreviation) for two years. His main areas of interests are robot intelligence, industrial instruments, and control.

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