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A Novel Smart Shoe Insole for Gait Analysis

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Abstract

This paper introduces a novel, robust, and electrically noise-resistant footwear sole using piezoelectric sensors for gait analysis. While numerous piezoelectric footwear energy harvesters have been reported in the literature, they have all faced a common challenge—the low mechanical strength of piezoelectric sensors required to withstand the weight of a human. Our results demonstrate that coating the piezoelectric sensors with silicone rubber not only significantly enhances the strength of the designed sole against mechanical loads but also the optimal value of the hardener-to-resin ratio, resulting in remarkable improvements in sensor efficiency. An electrical circuit is implemented for data acquisition in the test setup and revealed that the silicone coating of the piezoelectric sensors contributes to a reduction in noise levels in the output signals. Various tests have been conducted to investigate the pressure distribution on the foot's sole and its temporal sequence. Additionally, the system accurately detects ankle-twisting incidents, showcasing its potential to diagnose joint-related issues. This innovative sole design holds promising applications, including real-time gait analysis, sports performance tracking, pressure mapping, and rehabilitation purposes.

Keywords: Piezoelectric; Gait; Silicone resins; Arduino Uno.

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1. Introduction

These days, wearable electronic devices have found more and more applications in our lives, from vehicles and watch to applications in medical cases that can help us to find out some abnormalities and problems by examining body movements and taking action to fix them faster; for example the type of weight distribution on different parts of the foot in those who have flat soles, or braces, etc. is different from healthy people, and therefore, if a smart shoe shows the weight difference in the position, it can help to diagnose this abnormality.

Neel Shah et al. have demonstrated a novel approach to health monitoring and energy harvesting using IoT. They have developed a smart shoe that tracks the user's health and generates electricity through activities such as walking and running. This power generation is facilitated by piezoelectric plates located at the base of the shoe's sole. The smart shoe presented by Shah and his team could pave the way for future research in wearable health devices (WHDs). [1] Among all the methods used in wearable electronics, it is necessary to use sensors with high accuracy and suitable for performing tests, one of which is IMU.

A group of researchers, led by Niharika Gogoi, developed a unique insole structure that combines IMU (inertial measurement unit) and piezo sensors to measure an individual's gait at three specific points on the sole of the foot - the heel, toe, and metatarsal. The research highlights that the results obtained are influenced by the pressure distribution of the sole of the foot and the manner and force of walking. The study included three different observers of varying ages and weights, and it was found that the metatarsal bone experiences the highest pressure during walking. The piezo sensor and IMU produced consistent patterns of results. [2] Talib et al. conducted a study wherein they placed three piezoelectric sensors on the soles of both feet. They analyzed the distribution of force and applied pressures in five different situations, namely standing on both feet, standing on one foot, walking, heel strike, and toe-off. The researchers examined the areas of the soles of the feet, and the results showed that the force on both legs is the same when walking. During the heel strike, the sensor on the heel showed more force than the other two sensors. When performing a toe-off activity, the sensor located in the front part of the foot sole measured the most force. [3]

A Gait Shoe has been developed by Bamberg et al, which is a wireless wearable system equipped with an unparalleled number of sensors designed to capture data that can characterize the gait of both feet. Preliminary results suggest that the Gait Shoe could be a significant research tool. It has the potential to enable gait analysis in unconventional ways, such as over extended periods and in home environments, or through the use of pattern recognition. Furthermore, it can provide real-time feedback for applications in fields like sports medicine, electro-stimulation, and physical therapy. [4] Various types of piezoelectric materials, including natural and artificial piezoelectric, are widely utilized in wearable electronics. The primary objective of artificial piezoelectric manufacture is to enhance the material's sensitivity and power to achieve clearer results in various applications. Shoes and tiles are two of the notable uses of piezoelectric. Selleri and their group have successfully integrated a flexible piezoelectric sensor made of nanofibers into a composite material. This nanofiber mat was embedded within a blend of epoxy resin and polyurethane. The resulting sole was then affixed to an ankle-foot prosthesis, and compression tests were conducted by applying an oscillating load between 200 and 800 N at a frequency of 1 Hz to simulate the gait cycle. In robotics, these piezoelectric nanofiber mats can serve as tactile sensors for prosthetic hands, creating a network of pressure receptors in the fingers. The laminate's self-sensing capability at low frequencies can be utilized to monitor quasi-static loads, such as controlling gripping force. [5] One of the challenges of using piezoelectric in wearable electronics is that some of these materials should not be in direct contact with the human skin due to the presence of toxic materials and an interface layer is needed. This layer should be selected in such a way that it is able to protect the piezo from breaking in extreme movements and bends. Among other important points, it is important to choose a layer with an amount of elasticity such that it does not dampen the impact and mechanical pressure and transfer it to the piezo sufficiently to be able to check the results.

In this paper, our approach was to set up a gait analysis shoe sole using piezoelectric sensors made of lead zirconate titanate (PZT) embedded in silicone rubber. a person's walking pattern was investigated through this device. the data of piezoelectric coins can be checked at any time while a person is walking, and the amount of movement of each piezoelectric shows the amount of pressure applied to that area of the foot, which can be used to detect all kinds of abnormalities and problems in the pattern of walking, jumping, running, sitting, etc. in people, and in other words, it was used as a medical diagnostic device.

2. Materials and methods

2.1 Piezoelectric

The word "piezoelectricity" has its roots in the Greek word for "squeeze or press"[6]. Piezoelectric materials generate an electric field when they are mechanically deformed. This field is created by a lack of inversion symmetry within the material, which produces an electric dipole that changes in strength when the material is bent or strained.

Piezoelectricity is a fascinating phenomenon that can be classified into three distinct subcategories: ferroelectric, pyroelectric, and piezoelectric [7,8]. Each subcategory boasts its own unique traits. For example, ferroelectric materials are piezoelectric and exhibit spontaneous polarization in the absence of strain. There exists a wide range of materials that possess piezoelectric properties, including natural crystals such as berlinite, quartz, and sugarcane, as well as synthesized materials like barium titanate (BaTiO3) and certain polymers. Interestingly, some of these materials even surpass quartz in their impressive piezoelectric properties.

There are two categories of the piezoelectric effect: the direct and inverse piezoelectric effect. The direct piezoelectric effect [9] was mentioned earlier and refers to the creation of an electric potential difference from an applied stress. On the other hand, the inverse piezoelectric effect involves a change in the shape of certain crystals, ceramics, and polymers due to the application of an electric potential difference. connecting the opposite faces of these materials to an alternating electric potential difference, they undergo an alternating deformation and vibrate.

The relationship between the electrical and elastic properties of piezoelectric materials is in the form of equation (1):

$$\left[D\ S\right] = \left[d\ \varepsilon^{T}\ s^{E}\ d^{t}\right] = \left[T\ E\right] \qquad (1)$$

Where D represents electric displacement and E represents an electric field. S represents pressure and T represents stress. d and dt are the matrices for the piezoelectric charge coefficient and its transpose; $\mathcal{E}^{T}$ is the dielectric permittivity under a constant stress T; $s^{E}$and is the elastic compliance under a constant electrical field E.[6]

2.2 Silicone resins

Silicone resins are a group of resins that show good resistance to chemicals and heat due to the presence of silica compounds. These types of resins are used in paints that require high heat resistance and also have wide applications in electrical industries. RTV-2 silicone resin is also used for moulding resin and plaster materials and is one of the available and not-so-expensive resins that is sold with its hardener. Hardener is used to cure and harden the resin, and in common applications, it is mixed with 2 to 5% of hardener; But since it causes shock damping in applications similar to this research as well as in energy harvesting research, it is better to use higher percentages of hardener so that the hardness of the resin reaches an optimal state that provides the necessary flexibility to protect piezoelectric coins and the possibility of bending. to give them and transfer the incoming force well to the piezoelectric coins. According to our conducted tests, the amount of 22% hardener was found to be the most suitable state for the intended use of this resin.

2.3 Moulding and Arrangement of piezoelectric pieces

In this research, the initial mould was made from corporate foil in the shape of a shoe sole, and then a layer of RTV-2 silicone resin with % 22 hardener was poured, and 6 piezoelectric coins with a diameter of 2.7 cm, each soldered to two wires were placed as shown in the Fig. 1 and covered with a second layer of resin. This structure should have been placed in a stable space and relatively constant temperature for about 24 hours to fully cure and prepare to start the tests.

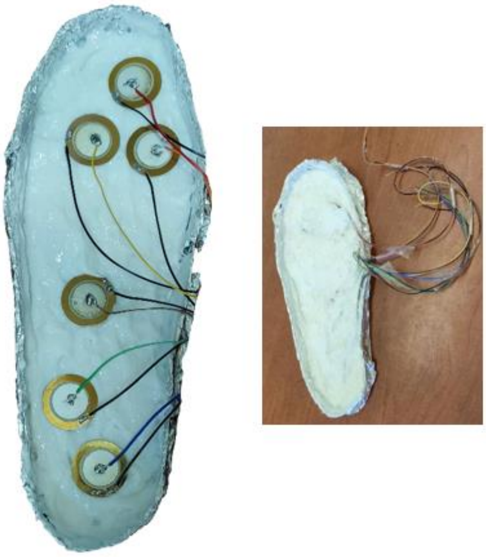


Figure 1. The insole and the position of each piezoelectric in the sole

Table 1 indicates the numbering of piezoelectric as well as corresponding analogue port of Arduino.

Table 1: Sensors numbering

Piezoelectric number	Analogue Port of Arduino	Wire Color
0	A0	red
1	A1	orange
2	A2	yellow
3	A3	brown
4	A4	green
5	A5	blue

3. Tests

All piezoelectric elements are paralleled with 3 mega ohm (Ω) resistance. The voltage at both ends of the resistors will be reported using Arduino Uno. This board includes multiple AC and DC outputs, which makes it suitable for projects such as this. In this series of experiments, its analogue ports have been used to obtain the piezoelectric voltage. In this test, it should be noted that the upper limit of the voltage that can be read from the Arduino is 5 volts. Due to the voltage divider principle, the voltage at the junction between R_1 and R_2 will be a fraction of the input voltage based on the ratio of R_2 to the total resistance $(R_1 + R_2)$. In this case, the voltage at the junction will be:

$$V_{out} = V_{in} \frac{R_2}{(R_1 + R_2)} \qquad (2)$$

To create a voltage divider circuit for an Arduino Uno with a maximum input voltage of 15V from a piezoelectric sensor and ensure that the output does not exceed 5V, can use two resistors. Select two resistors, R_1 and R_2. Resistance R_1 should have a much higher resistance than R_2, and the specific values will depend on the maximum current the piezoelectric sensor can provide. With the chosen resistor values, the output voltage can be calculated as follows: $V_{out} = 5V$. This ensures that the output voltage does not exceed the Arduino Uno's maximum input voltage tolerance, which is 5V. Figure 1 shows the sketch of the voltage divider circuit used for each piezoelectric.

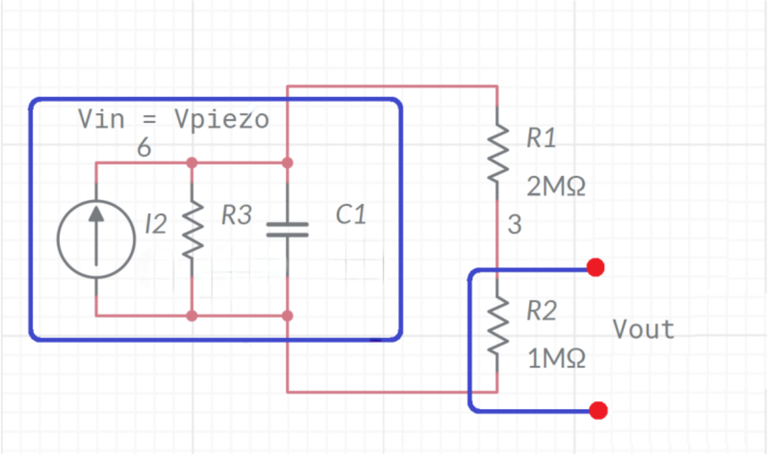


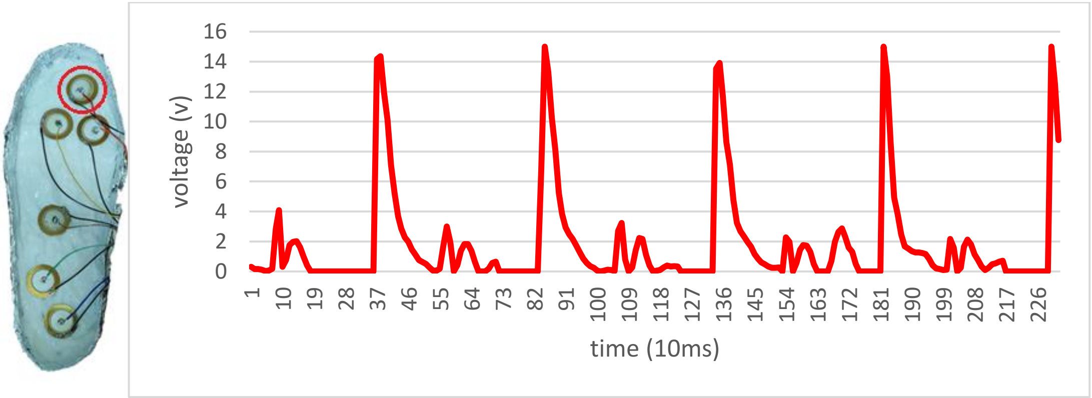
Figure 1. Schematic of the voltage divider circuit used for each piezoelectric

As mentioned above, 6 piezoelectric elements were put into a mold for shoe insoles for size 42 shoes. According to the map of pressure distribution in the soles of healthy feet, the piezoelectric elements were placed where the pressure was the most, or useful information about walking patterns could be obtained. It was decided to use a 22% ratio of hardener to resin in order to create this insole. After the wires are connected, the insole can be used in regular size 42 shoes as shown in Fig.3.

Figure 3. The insole in use

This new insole was put to the test. Each piezoelectric is connected in its resistive division circuit and connected to the analogue inputs of the Arduino, so that the output of each one could be studied. In the practical test of this insole, one can understand the walking pattern of a certain individual. For the purpose of testing this device while walking, the board and Arduino Uno was strapped to the person's foot, and the data was collected while a 95kg person was walking on a treadmill, with an approximate speed of 2km/h. The output signal of all 6 piezo-sensors is plotted in Fig.4.

(a)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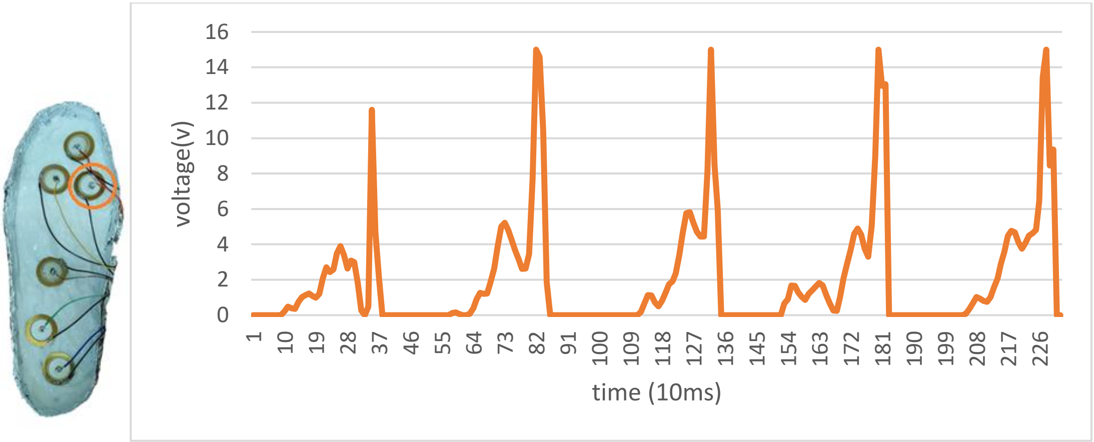
(b)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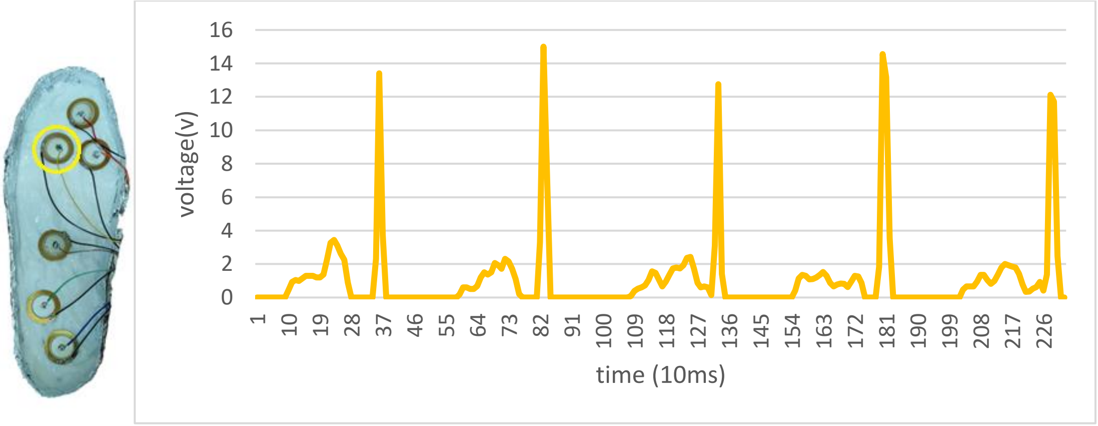
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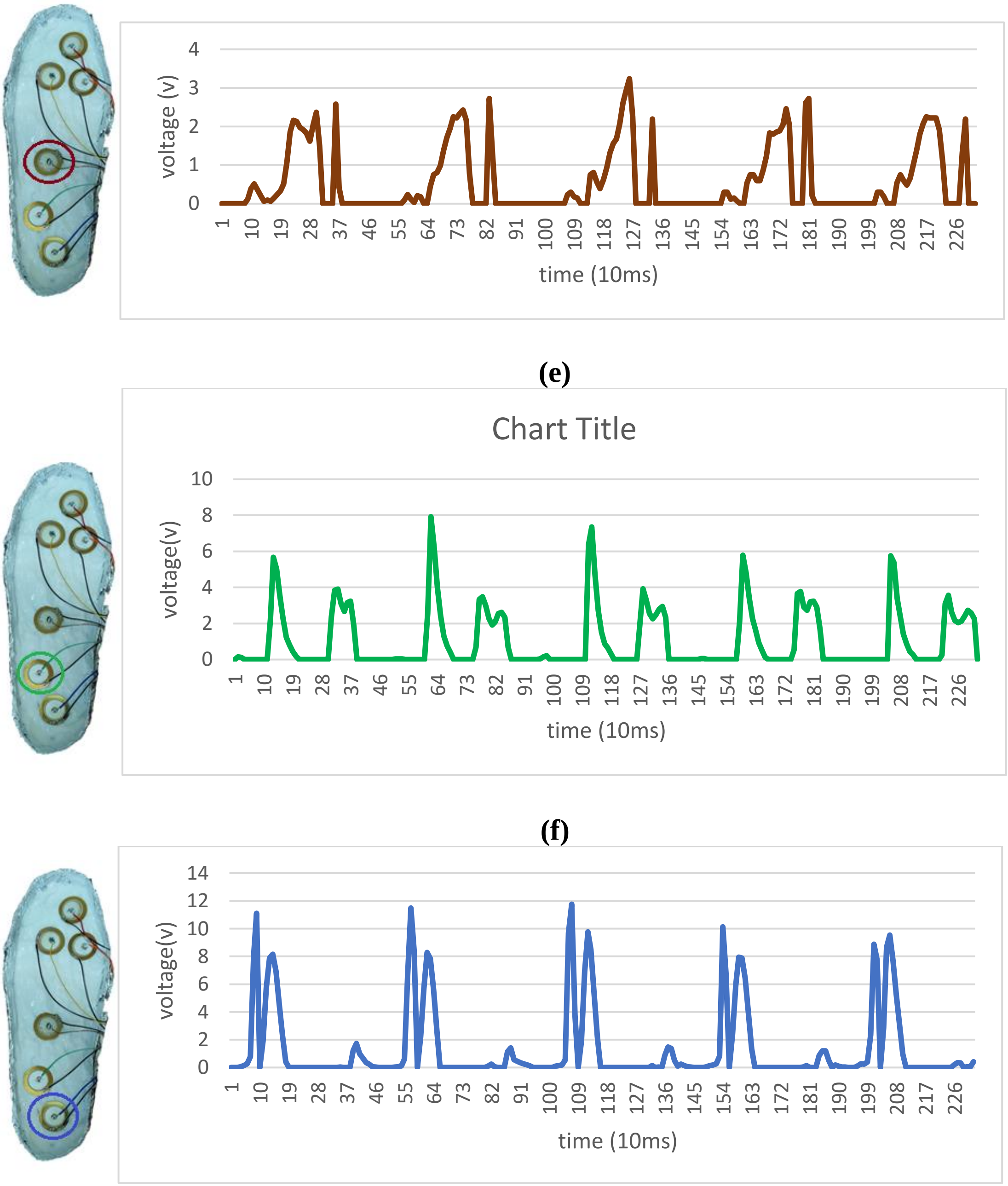

(e)

(f)

Figure 4. Data acquired from each piezoelectric element separately.

Figure 4 reveals several salient and noteworthy observations. Firstly, the repetition of motion patterns within these diagrams is conspicuously apparent. This is primarily attributed to the system's resilience in the face of diverse noise sources and its commendable data transmission capability. Such discernible patterns and data endow considerable value for orthopedics, kinematics, and many other perspectives. Secondly, it is evident that the highest sensor outputs are associated with the forefoot region, while the lowest outputs correspond to the midfoot area. This observation can be attributed to the more bending of the forefoot during walking and the reduced pressure on the midfoot piezoelectric sensor due to the midfoot arch. These findings, in addition to various biomechanical interpretations and gait analysis perspectives, can greatly be useful in the optimal design of piezoelectric shoe inserts for energy harvesting purposes.

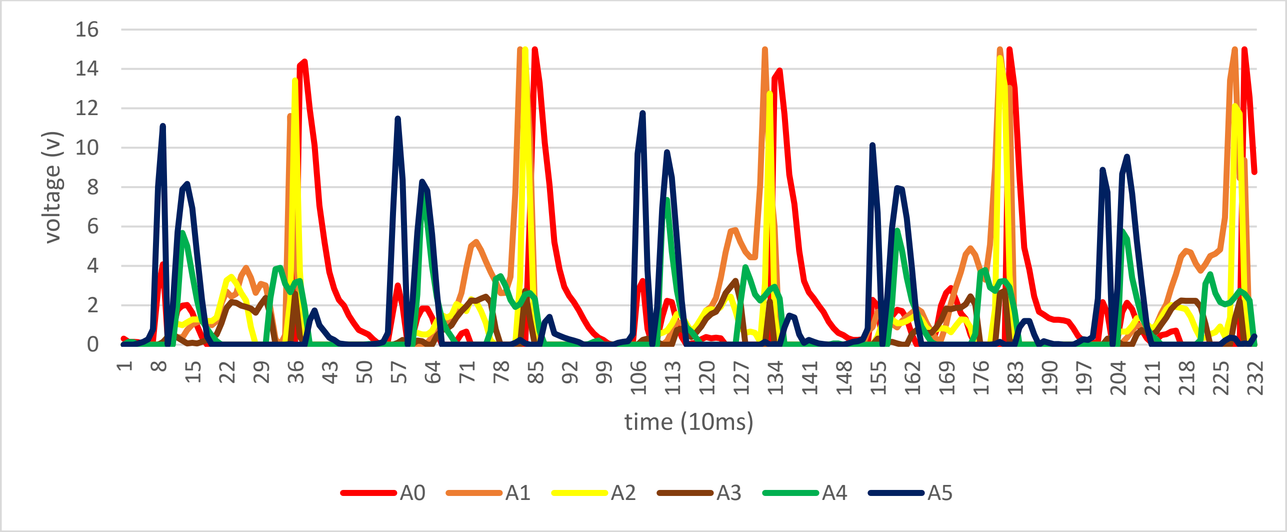

Figure 5. Comparison of sensors outputs for normal walking

Comparing the outputs of all sensors on a single graph as Fig. 5, can reveal other remarkable findings. For instance, the transfer of pressure from the heel to the forefoot is evident in this figure. Other than recognizing patterns, this system can identify rapid changes, i.e., losing balance. For example, the subject sprained their ankle while walking and struggled to walk for a few seconds, which can be seen in Fig.6.

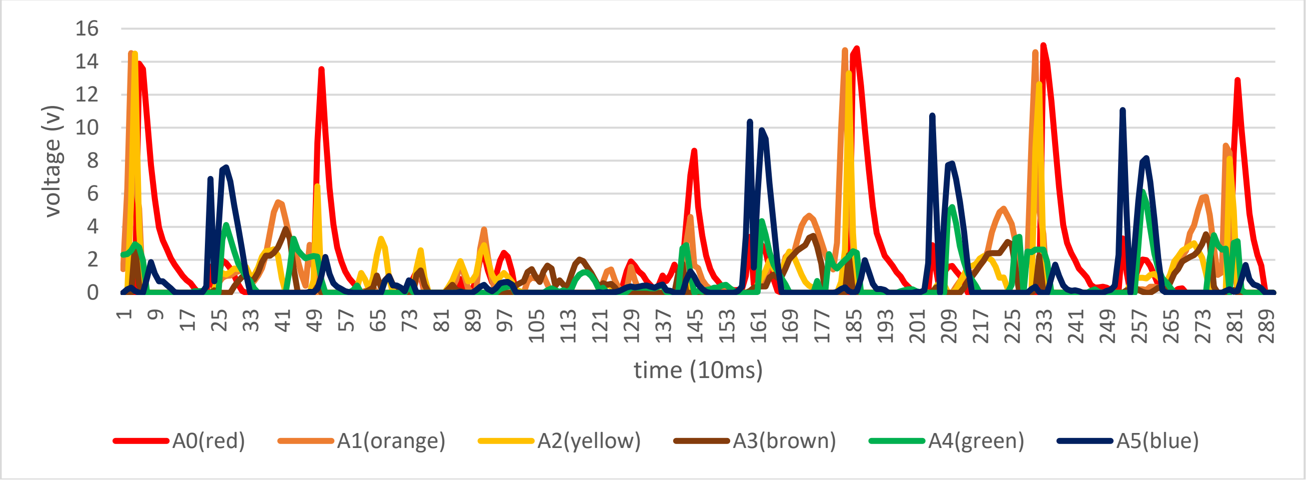

Figure 6. Results for ankle twisting incidents

Figure 6 illustrates that this smart shoe insole can be utilized not only for health monitoring applications but also for in-depth investigations into pressure distribution prior to ankle twisting incidents leading to novel insights regarding the causes and severity of ankle twists.

Conclusion:

This paper successfully demonstrates the feasibility of utilizing piezoelectric shoe inserts for gait analysis and biomechanical investigations. Furthermore, this study introduces the use of silicone resin for coating the piezoelectric sensors, offering numerous advantages, including increased durability, reduced sensor noise, and better compatibility with the human body.

To assess the functionality of the smart sole, two tests were conducted, and the time history of pressure distribution on the foot's sole is reported for two walking conditions: normal walking and walking with an ankle twist. The results of this study hold promise for a wide range of applications, particularly in health monitoring, especially among elderly individuals, sports analysis, rehabilitation, and as a valuable adjunct tool for orthopedic practitioners.

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