A lamination-based piezoelectric insole gait analysis system for massive production for Internet-of-health things

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Abstract
Gait analysis has been proved to be a powerful and efficient means for health monitoring. Variety of nervous system diseases and emergencies can be detected by interpreting plantar stress distributions. Among gait analysis techniques, piezoelectric insole architectures receive boosting attentions due to its convenience for users to wear and its long-term and real-time monitoring ability. However, the complex integration of piezoelectric insole architecture limits its successful use for massive production for the Internet-of-health things (IoHT). Hence, in this article, we present a flexible printed circuit board and lamination-associated technique, which presents high detection sensitivity at 0.1 N, satisfying the need for assisting nervous system disease diagnosis, and showing strong potential for commercialization.

Keywords
Insole gait analysis, piezoelectric films, flexible printed circuit board, lamination and plantar stress sensing

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Introduction
Internet-of-health things (IoHT) have been experiencing significant expansion with the rapid development of Internet- and sensor-associated technologies. Among various IoHT techniques, wearable electronic-based products dominate markets, for example, smartwatch. However, traditional wearable products merely detect few body signals, for example, heart and respiration rate, limiting use for comprehensive studies of human mental and physical conditions. In this instance, gait analysis techniques embrace fast growth, owing to its strong correlation with a vast number of illness (such as parkinsonism,¹ cerebral palsy² and Alzheimer’s disease³) and human behaviors (e.g. fall risk assessment⁴ and quality of life).⁵ The gait signal data were from the authors.

In the past decades, there have been intensive researches on wearable accelerometer/gyroscope-based gait analysis systems. However, the limited number of parameters (stride length, pace, and body sway)⁶–¹¹ is insufficient for disease diagnosis due to the lack of disease analysis required details.¹² In order to obtain sufficient gait information, insole plantar pressure sensors gain increasing attention in recent years.¹³–¹⁵

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Techniques for insole plantar pressure measurement include capacitive, piezoresistive, and piezoelectric architectures. Among them, the last one triggers broad interests due to its intrinsic performance in converting mechanical deformation to electricity passively, extending battery’s life time. Xin et al.\textsuperscript{16} developed slippers with flexible piezoelectric sensors, in which a single polyvinylidene fluoride (PVDF) is integrated into the sole of the slippers for detecting heel strike and toe-off moments by monitoring the walking-induced flipper bends. In a study by Zhou and Hu,\textsuperscript{17} PVDF films co-operated with orthogonal accelerometers and gyroscopes and electric field height sensors for outdoor multi-functional use. Szary\textsuperscript{18} placed four discrete piezoelectric copolymer (PVDF-TrFE)-based sensors at the toe, first and fifth metatarsal head (MTH) and heel to retrieve useful information.

Although promising results have been demonstrated in the literature, piezoelectric commercial products have not been successfully accepted by the market. One of the critical factors is the inability for massive production. Hence, Rajala et al.\textsuperscript{19} claim that the future piezoelectric insole system requires printing electrodes on the piezoelectric films, for a fast, large area, low-cost production for the manufactory. However, piezoelectric films are not high-temperature-tolerant materials. When printing temperature is near or above the Curie point, damage of polarization starts to appear, resulting in the lose of piezoelectric ability. Alternatively, with the mature development of a flexible printed circuit board (PCB) technique, different electrode patterns can be efficiently designed for studying various gait-related diseases. Meanwhile, lamination techniques allow fast integration of electrodes and piezoelectric films, potentially supporting massive production, which is essential for developing gait analysis applications in IoHT.

In this article, a thin and flexible insole sensor is developed to measure plantar stress. The gait signal data were from the authors. Electrode patterns of 36 detecting points are designed and printed as on a PCB to detect the pressure associated with nervous system diseases. The device achieves high sensing sensitivity at 56 mN for normal stress. Application of vacuum lamination techniques makes the fabrication process of device rapid and convenient, enabling large-scale production of the system. The proposed method gives a satisfying performance in experiments, meanwhile demonstrating great commercial potential in various applications. Compared with the conventional gait analysis system, not only does the presented system detect plantar pressure accurately, but it consumes less energy due to the passive detection mechanism of piezoelectric materials.

This article is structured as follows. Section “Literature review on piezoelectric insole techniques” reviews the current piezoelectric insole systems. Sections “Device fabrication” and “Readout circuitry and system integration” describe the device fabrication process and readout circuitry. Results and discussion are provided in section “Results and discussion.” Finally, conclusions are drawn in section “Conclusion.”

**Literature review on piezoelectric insole techniques**

Plantar pressure reveals the physical condition of human bodies such as walking and running, and thus gains the attention of researchers in different areas. Measurement of plantar pressure has become a popular topic in the past few decades, and a variety of piezoelectric-based techniques have been developed.

At the early stage of planter stress detection, only normal stress sensing is supported. For example, Munk-Stander\textsuperscript{20} evaluated the piezoelectric film sensors for insole pressure measurement. The author designed a 10 × 10 mm\textsuperscript{2} PVDF sensor with 52-μm thickness to measure the plantar pressure, though the sensitivity was hindered by crosstalk raised by the co-existence of piezoelectric $d_{33}$ and $d_{31}$ coefficients, a satisfying result was still obtained for distinguishing different motions. To pursue high detection accuracy, minimization of crosstalk becomes significant. Some researchers stuck thick metal disk to the sensors to prevent the piezoelectric film from bending, in order to reduce charges generated by shear stress. For instance, Klimiec et al.\textsuperscript{21} used four printed silver electrodes with thin metal plates attached underneath the sensor positions to measure the normal pressure on the heel, medial midfoot, metatarsal, and great toe. An alternative way, namely integrating rigid electrodes in sensors, was proposed by Nevill et al.\textsuperscript{22} and Klimiec et al.\textsuperscript{21} However, the rigid electrodes bring uncomfortable feelings to users.

With the increasing need for disease diagnosis, detection of plantar shear stress is desired. Hence, some literature presented plantar pressure sensors that can measure normal and shear stress simultaneously. Existing systems for measuring triaxial forces usually stack several discrete commercial sensors, which are polarized in different directions,\textsuperscript{23} or arrange them in parallel in the same plane,\textsuperscript{24} adjoining to each other.

Although varieties of piezoelectric-based gait analysis prototypes have been developed, commercialization is still not successful. A major challenge is the complex assembling process, where people traditionally glue single piezoelectric sensors at different planter locations, resulting in a huge workload during massive production. Therefore, Rajala et al.\textsuperscript{19} claimed that a potential solution is to print electrodes on the piezoelectric film directly.

In 2009, Kärki et al.\textsuperscript{25} attempted to use ink-jet printing to fabricate metal electrode on PVDF material. However, due to the thermal stress raised from the high temperature (150°C) during the electrode printing process, the sensitivity of the sensor was decreased to...
10%–20% of traditional manufacturing methods. An alternative way to prevent thermal stress during manufacturing is to use solution-processable non-metallic electrode\textsuperscript{26} (such as PEDOT: PSS ink, CNT-cellulose nanocomposite ink and silver flake ink).\textsuperscript{26,27} Nevertheless, their conductivities cannot be compared to metal electrodes.

Based on the literature, printing electrodes on piezoelectric films is not mature enough for massive production; therefore, people have started to seek other manners. It has been noticed that lamination is a reliable technique for assembling electrodes with functional films. Some recent work\textsuperscript{28} demonstrated lamination-based techniques for integrating graphene and indium tin oxide (ITO) electrodes with PVDF films for touch panels, providing a potential solution for piezoelectric insole systems. The provided lamination technique does not corrode electrodes, nor does it affect the flexibility or conductivity of the films, as opposed to traditionally glueing thin-film materials together.

**Device fabrication**

**Device architecture**

The developed plantar pressure transducer consists of five thin films. The middle PVDF piezoelectric film, with a thickness of 50 $\mu$m, is covered with patterned electrode films on its upper and lower surfaces, and outermost layers are insulated plastic films for protection, as conceptually shown in Figure 1(a).

The insole distribution map of sensors is shown in Figure 1(b). Each electrode is designed as a round-shaped thin plate with a radius of 4 mm and a thickness of 100 nm. In total, 36 electrodes are distributed at predetermined plantar locations. According to the foot anatomy\textsuperscript{29} and gait analysis in previous studies,\textsuperscript{30} the electrodes are mainly settled at areas of the heel, the front foot soles, and the toes, where pathological parameters of human beings could be well represented. Furthermore, the specific location of each electrode is carefully arranged around the high plantar pressure regions, according to Orlin and Mcpoil.\textsuperscript{31} The area covered by electrodes is subjected to more than 80% of plantar pressure in motion, providing sufficient useful information for clinicians for neurological diseases diagnosis. Figure 1(c) shows the electrode patterns of the sensing layer. Size of the layer shown is 210 $\times$ 297 mm$^2$, corresponding to the American shoe size of 38.

**Fabrication process**

A flexible PVDF thin film with a thickness of 50 $\mu$m serves as the sensing layer, covered by two electrode layers. The lower one, settled as the ground electrode, is a piece of copper foil. The upper electrode layer provides 36 measuring points and their connection lines. Each measuring point is round shaped with radius of 4 mm. Due to the arrangement of the electrodes, the spacing between two adjacent electrodes varies, the minimum spacing is 4.5 mm. Patterns of the electrode are designed with computer-aided design (CAD) software and then fabricated into flexible PCBs with the method of etching copper.

Afterwards, the lamination process is carried out by a stitching and defoaming machine (SMD, Shenzhen, China). The stacked films are put on the working platform and proceed to compaction. Laminating pressure and duration are, respectively, 0.4 MPa and 0.8 s, under the temperature at 100°C. The films are laminated every two pieces. Physical map and the photograph of one fabricated device (left foot) are shown in Figure 2.

**Readout circuitry and system integration**

**Readout circuitry**

Figure 3 shows the schematic of the readout circuitry. When a dynamic pressure is applied to the insole device, charges generate on surfaces of PVDF films and are collected by electrodes. A TL062 chip-based charge amplifier is designed to convert the obtained charges to voltage amplitudes which are then amplified to desired levels.
The collected charges $q_p$ is proportional to the force applied, ignoring the small crosstalk in other directions

$$q_p = d_{33} \times F$$  \hspace{1cm} (1)$$

where $F$ refers to the normal stress, and $d_{33}$ indicates the piezoelectric constant.

Proper selection of feedback capacitance ($C_f$), feedback resistance ($R_f$), and input resistance ($R_i$) is performed, to ensure both high amplification factor and good system bandwidth. In the provided readout circuitry, the amplifier has the lower cut-off frequency of 0.66 Hz and the upper one of 1500 Hz, and an amplification factor of 200 is obtained.

The outputted voltage signal of charge amplifiers is selected by a high-speed transistor–transistor logic (TTL)-compatible field effect transistor (FET) multiplexer (SN74CBT16214C) in sequence and then converted to a digital signal by a 16-bit analog-to-digital converter (ADC; ADS1115). An STM32 single-chip microcomputer provides the function of modular control and data processing. The normal stress from 36 channels, calculated by the microcomputer, is then transmitted in serial mode through a Bluetooth module (HC06). MATLAB software installed in the upper computer receives and stores data via Bluetooth port in real time. The plantar pressure data can be further analyzed by doctors to realize disease prediction and diagnosis for IoHT applications.

**Results and discussion**

**Device characterization**

The insole plantar pressure sensing system detects normal stress changes. Dynamic tests are implemented by an electronic push-pull gauge (HANDPI, Zhejiang, China). The sensor was placed horizontally on the worktable and each sensing point was tested separately. In one test, the force applied increased from 0 to 40 N...
by the rate of 10 N/s. Repeat the test 20 times at each measuring point and average the output voltage of the measurement.

Measuring results are provided in Figure 4(a). The left heat map shows responsivities of the 36 measuring points on the left foot, indicating that our sensors at all plantar areas work well. Square array in the heat map (from left to right, from bottom to top), is arranged in the order shown in Figure 1(b). The right fitting diagram demonstrates the result of a sensing point (No. 16), where the output is recorded every increase of 5 N.

The responsivity we expect, through theoretical calculations, is around 870 mV/N. However, average responsivity of the transducers is 693.1 mV/N experimentally. When signal-to-noise ratio (SNR) is 0 dB, the detection threshold is 0.056 N. A possible reason for the decrease may arise from piezoelectric constant changes during the high-temperature and high-pressure compression.

System calibration

A practical plantar pressure measuring experiment with the developed system is carried out. When a user steps on the insole system, real-time normal stress information is obtained (Figure 4(b)). A plot for a walking pattern is shown in Figure 4(c). In order to present a complete plantar pressure-distribution plot, stress between electrodes is estimated by a smoothing algorithm proposed by Pataky, making the measured results more elaborate and complete.

With our high-speed ADC and data processing algorithm, real-time monitoring of plantar pressure can be realized. Figure 5 shows the variation of stress with time in four valuable plantar areas (first toe, first metatarsal bone, lateral plantar, and center of heel) during a walking event. Purple and green lines are corresponding to pressure obtained under the right foot and the left foot, respectively.

Discussion

Normal stress at 36 specific plantar points is successfully detected in the developed system. In order to calculate the pressure value from output voltage, sensitivity and responsivity of each measuring points are measured, respectively, achieve 693.1 mV/N and 0.056 N. Proper parameter selection of the charge amplifying circuit ensures the high sensitivity of the presented insole system. The allowance of precisely measuring small changes makes the system suitable in medical diagnostics. With a ground electrode to avoid crosstalk, there is just a slight responsivity difference between the individual transducers.

During the fabrication process, pre-tightening force and temperature rise may affect the performance of the sensor. Nevertheless, the high sensitivity and
responsivity show that the lamination method does not significantly harm the performance of the device.

The following data processing algorithm enables the system to calculate the vast majority of plantar pressure, offering more possibilities for the diagnosis and treatment of neurological diseases.

Conclusion

In this article, we present a piezoelectric plantar pressure-sensing system that satisfies the need for large-scale production. Here, flexible PCBs serve as electrodes and substrates, and lamination technique is applied during the fabrication process. The presented work overcomes the limitations of previous integrating techniques in terms of large manufactory complexity and achieves high detection sensitivity of 0.1 N. The work in this article shows excellent commercial potential for piezoelectric insole devices, and broad application prospects, such as nervous system diseases diagnosis, sports training improvement, and footwear design.

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