Smart Insole: A Wearable Sensor Device for Unobtrusive Gait Monitoring in Daily Life

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***Abstract*—Gait analysis is an important medical diagnostic process and has many applications in healthcare, rehabilitation, therapy, and exercise training. However, typical gait analysis has to be performed in a gait laboratory, which is inaccessible for a large population and cannot provide natural gait measures. In this paper, we present a novel sensor device, namely, Smart Insole, to tackle the challenge of efficient gait monitoring in real life. An array of electronic textile (eTextile)-based pressure sensors are integrated in the insole to fully measure the plantar pressure. Smart Insole is also equipped with a low-cost inertial measurement unit including a three-axis accelerometer, a three-axis gyroscope, and a three-axis magnetometer to capture the gait characteristics in motion. Smart Insole can offer precise acquisition of gait information. Meanwhile, it is lightweight, thin, and comfortable to wear, providing an unobtrusive way to perform the gait monitoring. Furthermore, a smartphone graphic user interface is developed to display the sensor data in real-time via Bluetooth low energy. We perform a set of experiments in four real-life scenes including hallway walking, ascending/descending stairs, and slope walking, where gait parameters and features are extracted. Finally, the limitation and improvement, wearability and usability, further work, and healthcare-related potential applications are discussed.**

***Index Terms*—Gait analysis, inertial measurement unit (IMU), plantar pressure, Smart Insole, wearable devices.**

I. Introduction

GAIT is the movement pattern of the limbs of humans during locomotion. People use a variety of gaits, selecting gait based on speed, terrain, the need to maneuver, and energetic efficiency. Several human factors, such as aging, injuries, and pathological diseases, may change a person's walking style into a different one, either permanently or temporarily [1]. It has been proved that change in the gait is an early indicator in major events such as falls and chronic diseases, which enables the timely preventive care [2]. Thus, gait analysis has become an significant human locomotion study to recognize normal or pathological patterns of walking, which enables a considerable amount of applications in medical programs, healthcare, rehabilitation, physical therapy, and exercise training. For example, gait analysis is a primary tool to assess fall risk and perform fall prevention in elderly healthcare [3], and diagnose the progress in Parkinson's disease.

To date, a variety of gait monitoring systems are investigated in the research community. Gait laboratories provide traditional environments for medical practitioners to observe the human gait motions. In a gait study, the subject wears reflective markers and walks on a pressure-sensitive mat, and the equipments capture the motion and extract the subject's gait parameters. Due to the burdensome equipment and unnatural environment, most of patients always feel uncomfortable during the data collection in a gait laboratory [4]. In most cases, they cannot walk in their own regular styles. Thus, the extracted gait features might always be biased, and even incorrect [5].

One alternative approach is to use video camera recording, which requires the subject confined in the camera surveillance area. The postprocessing of data involves complex video and image algorithms, making the system at a high price, such as Kinema Tracer system from Kissei. Some companies devised walking platform-based systems, e.g., Gaitway II from h-p-cosmos, WIN-POD from Medicapteurs, and smart carpet. When subjects walk on a treadmill or a special carpet, the gait and activity are recorded. This alternative is intermittent, lacks of the capabilities of to perform gait analyzing or fall warning in the practical walking scenes.

Recently, there is an increased attention on the wearable devices recently, which are widely used for gait analysis with the help of integrated inertial measurement unit (IMU) sensor. The data acquired from IMU can provide more accurate evaluation. However, these wearable devices usually require high adherence from the user as binding on the arm, waist, or thigh, which causes discomfort and raise the low-compliance issue. Such commercial products include the inertial sensor STT-IBS from STT and Xsens MVN body equipment from Xsens, etc.

In this paper, we introduce an insole-like wearable device, namely, Smart Insole, to address the aforementioned problems with gait laboratories, video and IMU, and enable gait monitoring in real life. This device looks similar to an insole and is able to monitor both inertial and pressure information from both feet. The Smart Insole system comprises a low-cost sensory insole and application software on both smartphone and computer for data storage and visualization. The insole consists of an array of sensors, an ultralow power microcontrol unit (MCU) and

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Bluetooth low energy (BLE) wireless transmission module, a channel multiplexer (MUX), a Li-battery, and a micro-Universal Serial Bus (USB) connector module. The application software provides visualization and a real-time guided feedback to the user. The data stored in secure digital (SD) card will be used to study lifestyle and health behaviors that facilitate new understanding and effective intervention options to promote individual independence. Specifically, Smart Insole can measure step counts, step pace, swing time, and center of pressure (COP) shifting velocity, etc., which can further infer the walking balance status and potential fall risk in real life. We evaluate Smart Insole with subjects in real life for gait monitoring, and the experimental results show the promising accuracy and usability. By using Smart Insole, users can monitor and analyze their gait in daily life instead of participating in a specific gait laboratory.

The organization of this paper is as follows. Section II introduces the related work. The design consideration and overview of the Smart Insole system are presented in Section III. In Section III-B, we demonstrate the hardware design including textile pressure array, inertial motion sensors, CC2541 and MCU, BLE, battery and micro-USB connector, and ergonomic design. In Section III-C, the software design is discussed including gait parameters extraction, software stacks and visualization. Section IV provides the evaluation of the Smart Insole system. Section V discusses the limitation and improvement, wearability and usability, further work and healthcare-related potential applications. Finally, the paper is concluded in Section VI.

II. Related Work and Design Comparison

A. Related Work

Recent researches have brought the idea of embedding sensors in shoes or insoles for human gait monitoring in academic society. Bamberg *et al.* [6] developed a wireless wearable system called "GaitShoe" for gait data collection outside the confines of the traditional motion laboratory, which includes accelerometers, gyroscopes, force sensors, bidirectional bend sensors, pressure sensors, as well as electric field height sensors. Noshadi *et al.* [7] proposed a lightweight smart shoe called "Hermes," to monitor walking behavior and use an instability assessment model to generate quantitative value with episodes of activity identified as important. Benocci *et al.* [8] used 24 hydrocells, which are piezoresistive sensors contained in a fluid-filled cell, embedded in an insole and an external IMU to monitor gait. Sazonov *et al.* [9] utilized five force-sensitive resisters integrated with a flexible insole and a 3-D accelerometer to identify common postures and activities of human using the support vector machines. All the aforementioned systems place the insole-like units inside the shoe, and the microcontrollers or IMU are strapped and mounted outside the shoe, which makes the system inconvenient to setup and discomfort to use in daily life. Shu *et al.* [10] developed an in-shoe monitoring system based on a textile fabric sensor array. This system can measure the spatial and temporal plantar pressure distributions. Kong *et al.* [11] used four air pressure sensors to detect human gait phase. Howell *et al.* [12] provides kinetic measurements of gait by using 12 force sensitive resistor sensors. However, these three systems cannot completely capture the gait characteristic due to insufficient IMU components.

There are also several commercial-off-the-shelf in-shoe devices available in the market. Pedar in-shoe system [13] embed single or multiple piezoelectric sensors into the shoe for real-time monitoring. However, the sensors are easy to damage under the pressure because of the body weight in a long term. The most recent insole product F-Scan from Tekscan [14] provides similar function and accuracy with our proposed system. However, due to lack of the wireless transmission module, the collected data cannot be transmitted to a smartphone for visualization in real time or uploaded to a data server for postprocessing.

TABLE I

A Competitive Analysis of Existing Methods

	Pressure	IMU	Usability	Wireless Trans.
GaitShoe [6]	*	*		*
Hermes [7]	*	*		*
Shu *et al.* [10]	*		*	*
Howell *et al.* [12]	*		*	*
Pedar [13]	*			
F-Scan [14]	*		*	
Smart Insole	*	*	*	*

B. Design Consideration and Comparison

A novel footwear device should be capable of providing fine-grained and accurate information on physical activities, which requires sensor rich design by integrating pressure sensors and IMU sensors. User experience is a normally ignored but critical evaluation metric in addition to the common performance metrics, we consider unobtrusive monitoring and usability in daily life are basic requirements for a satisfactory user experience. To achieve this goal, some functions must be offered including concise design without extra cable or device outside shoes or insoles, real-time visualization for activity data, and wireless transmission of data to smartphone and cloud platforms for further analysis. For the convenience of comparison, we summarize the features of existing methods in Table I for a competitive analysis. As shown in Table I, Smart Insole is able to obtain plantar pressure, IMU data, and provide satisfactory usability and wireless transmission function in the meantime. GaitShoe [6] and Hermes [7] are inconvenient to use in daily life. The systems proposed by Shu *et al*. [10] and Howell *et al*. [12] fail to measure IMU results. F-Scan [14] lacks of the capability of measuring IMU results and providing wireless transmission, while Pedar [13] can only provide pressure information without other additional functions or usability.

III. System Design

A. System Overview

The system architecture of Smart Insole is depicted in Fig. 1. There are three important subsystems in this architecture. The first subsystem is the low-cost sensor array including 48 pressure sensors, a three-axis accelerometer, a three-axis gyroscope, and

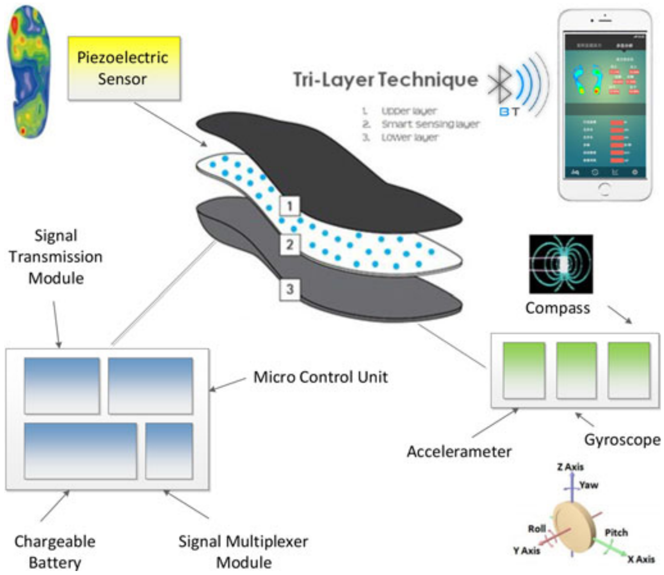
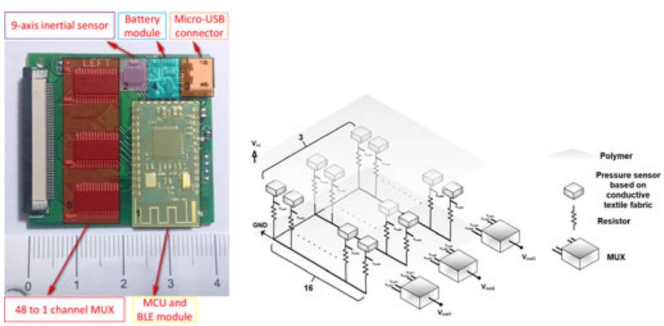


Fig. 1. System architecture of Smart Insole, which includes an array of sensors and a GUI.



(a) (b)

Fig. 2. PCB and pressure sensor array circuit of Smart Insole (a) The PCB design (b) The diagram of pressure sensor array circuit.

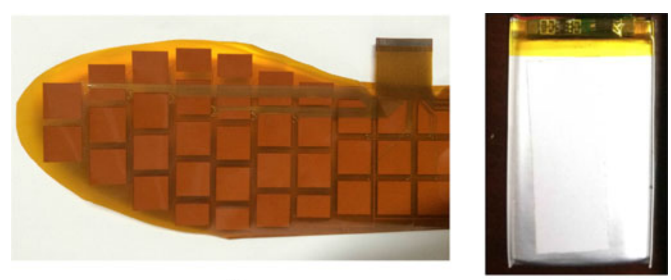
a three-axis magnetometer. The second is the data acquisition and transmission subsystem including an MCU and a Bluetooth module. The third is the visualization and graphic user interface (GUI) subsystem. The printed circuit board (PCB) for Smart Insole and its size are shown in Fig. 2(a), in which each component is labeled by rectangles with different colors. All components are placed in a 40 mm × 40 mm PCB. The integrated modules are 1) the MCU and BLE module, 2) the nine-axis inertial motion sensor, 3) the micro-USB connector, 4) the battery module, and 5) the 48 to 1 channel MUX. The design detail will be elaborated in the following sections. To provide a brief summary of Smart Insole, the overall system functional parameters are listed in Table II.

B. Hardware Design

1) Textile Pressure Array: The textile pressure sensor array is used to obtain the high-solution pressure map from feet, which is based on an advanced conductive eTextile fabric sensor technique [15] and can be efficiently integrated in the

TABLE II
PARAMETERS OF THE SMART INSOLE SYSTEM

Parameter	Description
Size	35-47 (European standard)
Thickness	2 mm
Number of pressure sensors	48
Range of pressure	30–1200 kPa
Response lag	< 5 %
Minimal bend radius	30 mm
Wired connection	Mini-USB
Wireless connection	Bluetooth low energy
Inertial sensors	One three-axis accelerometer, one three-axis gyroscope, and one three-axis magnetometer
Power supply	1200-mAh Li-battery, 3.7–4.2 V
Battery dimension	40 mm × 24 mm × 1 mm
Working during	24 h
IMU range	Accelerometer: ± 16 g Gyroscope: $\pm 2000^\circ/\mathrm{s}$ Magnetometer: $2500\ \mu\mathrm{T}$
IMU accuracies	Accelerometer: 7.81 mg/LSB Gyroscope: $0.061^\circ/\mathrm{s}/\mathrm{LSB}$ Magnetometer: $0.0625\ \mu\mathrm{T}/\mathrm{LSB}$
Quantization	8-channel, 12-bits
Storage	Flash memory
Voltage of A/D	0 –3.3 V
Driver	BSPP
Working Environments	Working temperature: -20–60 °C Storage temperature: -4–80 °C Working humidity: 10–90% (rh)



(a) (b)

Fig. 3. Pressure sensor array and rechargeable battery of Smart Insole (a) The pressure sensor array and circuit connection (b) The rechargeable battery.

Smart Insole system. ETextile is an industrial standard commercial product that is reliable for mission critical environments. It is a fabric coated with organic polymers. Bend, stretch and long-term use will not affect the sensor signal quality. The sensor array is coated with a piezoelectric polymer, and the initial resistance between the top–bottom surfaces is high. When extra force is applied on surface of the polymer, the inner fibers will be squeezed together and the resistance becomes smaller. As a result, the output voltage level will be high. The diagram of driving circuit is depicted in Fig. 2(b). The output of pressure sensors are chosen by three 16 to 1 channel MUXs (ADG706 from Analog Device) to connect to the analog-to-digital converter (ADC) input of the microcontroller. Each ADG706 contains 16 input channels and 1 output channel. Fig. 3(a) shows the real pressure sensor array and circuit connection. Each pressure sensor is with the size of 15 mm × 15 mm. With 48 sensors in total, more than 80% of the plantar area is covered.

2) Inertial Motion Sensor: The accelerometer and gyroscope are inertial sensors that measure the movement information of the subject. The magnetometer is used as the baseline when the inertial sensors (accelerometer and gyroscope) are being calibrated. We adopted BMX055 from Bosch Sensortec in the Smart Insole system, which integrates a 12-bit accelerometer, a 16-bit gyroscope, and a magnetometer in a single chip. The BMX055 communicates with the MCU using an interintegrated circuit (I2C) bus. Accelerometer, gyroscope, and magnetometer data in *X*-, *Y*-, and *Z*-axes are sampled simultaneously. With nine degrees of freedom motion sensing, the precision of motion activity can be safely achieved. The ranges of accelerometer, gyroscope, and magnetometer are ± 16 g, $\pm 2000\ ^\circ/\mathrm{s}$, and $2500\ \mu\mathrm{T}$, respectively, and the corresponding accuracies are 7.81 mg/LSB, $0.061\ ^\circ/\mathrm{s}/\mathrm{LSB}$, and $0.0625\ \mu\mathrm{T}/\mathrm{LSB}$.

3) CC2541 and MCU: The MCU and Bluetooth are implemented by a single device CC2541 from Texas Instruments. The CC2541 combines a radio frequency (RF) transceiver with an enhanced 8051 MCU, a 256-kB in-system programmable flash memory, an 8-kB random-access memory, a 12-b ADC, and a hardware I2C bus. The RF transceiver is a BLE and 2.4-GHz application compliant radio transceiver, and the radio operation is controlled by the BLE stack. The sensor data from three MUXs are digitalized by the eight-channel, 12-b, and 0–3.3-V ADC module. The sampling rate can be adaptive for specific applications, up to 100 samples per second (Hz). After that, the quantized sensor data are streamed to the smartphone in real time.

4) BLE: We used BLE as our transmission solution mainly for two reasons. First, BLE is power efficient, its properties of ultralow peak, average and idle mode power consumption gives the ability to run for long periods [16]. Thus, it has been widely used in Internet of Things devices. Second, support for BLE is available on most major mobile platforms including IOS, Android, Apple OS, Windows, GNU/Linux, it is almost the easiest way to design something that can communicate with all these platforms Therefore, the use of BLE in Smart Insole design enables maximum usability and adaptivity for users across various mobile platforms.

BLE operates between the frequencies of 2379–2496 MHz. The transmitter power of BLE is 0 dBm, and the receiver sensitivity is -91 dBm. The size of BLE packet is 20 bytes. The first four bits and last four bits of the first byte of each packet contain the sending sequence numbers and the packet sequence numbers, respectively. Forty-eight pressure data occupy three BLE packets and IMU data occupy two BLE packets. The last packet also contains the timestamp. The aggregator is able to connect to only one Smart Insole in one time, all the other access request will be rejected.

We conducted an experiment on the received BLE signal strength to find out the best BLE antenna location. We tested four different locations inside Smart Insole including toe tip area, heel area, medial arch area, and lateral arch area. In the experiment, the smartphone was set 1.5-m away from Smart Insole. The experimental result showed that the strongest signal strength is from antenna located at the toe tip area in all circumstances that with and without foot on top of the insole.

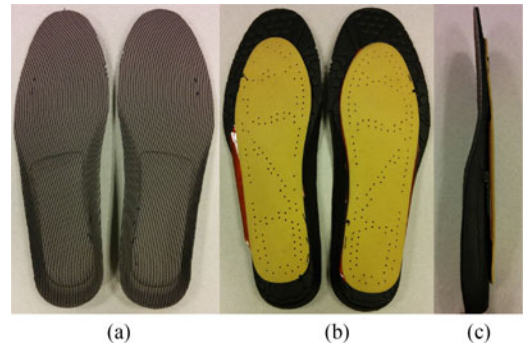


Fig. 4. Human ergonomic prototype of Smart Insole. (a) Front view. (b) Back view. (c) Lateral view.

This antenna setting has been adopted in Smart Insole. We also tested the drop-packet rate of BLE with a smartphone working inside the left pocket of pants. Various real-life scenes are considered including normal walking, running, ascending stairs, and descending stairs. The results showed that in all the real-life scenes the drop-packet rates were less than 2%.

5) Battery and Micro-USB Connector: The battery module contains a battery connector, a 3.3-V low-dropout regulator (LDO) (XC6206-3.3), a system power switch (SI2301), and a metal–oxide–semiconductor field-effect transistor (MOSFET). The MOSFET is controlled by the MCU for connecting and disconnecting power for nine-axis inertial sensor and channel MUXs. A rechargeable battery is connected to the battery module, which offers 3.7–4.2 V power supply. The output voltage is regulated by the LDO module down to 3.3 V. The dimension of the battery is $40\,\mathrm{mm} \times 24\,\mathrm{mm} \times 1\,\mathrm{mm}$, as shown in Fig. 3(b). The micro-USB connector is used for charging battery, programming CC2541, and online debugging.

We conducted three experiments to evaluate the battery lifetime in different operating modes including nonworking, offline working, and real-time working. In nonworking mode, Smart Insole was turned OFF, the battery lasted more than three months. In offline working mode, Smart Insole was powered on, but it did not connect to the smartphone, which means there was no data communication between them. In this case, the battery lasted more than four days. In real-time mode, Smart Insole operated normally and streamed data to the smartphone via BLE in real time, the battery lasted more than 24 h.

6) Package and Ergonomic Design: Integration insoles into shoes requires minimal extra effort to wear, thus reducing the burden and conspicuousness associated with activity monitoring and facilitating everyday use. Smart Insole is lightweight (< 2 oz) and thin, in which the insole with the pressure sensors weighs about 1 oz, PCB weighs about 0.4 oz, and battery weighs about 0.5 oz. Smart Insole is also convenient to use, which does not need calibration and only requires minimal setup procedures. Smart Insole is well packed with the help of professional package team, the package of Smart Insole is shown in Fig. 4. There are two layers on top of the pressure sensors and circuits. First, one layer made of waterproof polymer is to prevent water from permeating down to the sensor and circuit area. On top of it, there is another water absorbing layer made of antifriction fabric that can wick moisture away, so little sweat or water will not impact the performance of the insole. Smart Insole looks and feels similar to a normal insole without any extra cable, antenna, or adhesive equipment. The thickness of the metatarsal and toe area is 2 mm, and 2.5 mm for the heel area because of the additional cushion material on top layer of the insole for heel and device protection, which makes Smart Insole thin enough for unobtrusive use.

C. Software Design

1) Gait Feature Extraction: Gait analysis is a complicated process, and there is a considerable amount of significant features for identifying the normal and pathological walking patterns. Some are general and crucial for various applications, such as plantar pressure, step pace, swing time, stride length, and walking speed. Some only are applicable for specific domains. For example, the COP shifting velocity and the pressure balance of locomotion between two feet are important for fall prevention, and pressure hotspot mobility is critical for diabetes foot protection and ulcer prevention [17].

We list several general gait parameters for miscellaneous applications [10], [18] in the following sections, including the step count, step pace, duration of gait cycle, swing time, stance time, maximal pressure, average pressure, COP location, COP velocity, and COP trajectory. Such parameters are commonly used in gait analysis. To calculate temporal gait parameters, it is essential to detect heel strike and toe-off during a gait cycle. Once we are in possession of the heel strike and toe-off information, the temporal gait parameters can be easily calculated. The definitions of gait features are as follows.

1) Step count: The total number of steps.
2) Step pace: The number of steps in one minute.
3) Duration of gait cycle: The duration between two consecutive heel strikes.
4) Swing time: The duration between a toe-off and the following heel strike.
5) Stance time: The duration between a heel strike and the following toe-off.
6) Maximal pressure: The maximal pressure of all the sensors or in a specific area such as heel area or toe area.

$$\mathrm{P}_{\max} = \mathrm{Max}\left(P_1, \ldots, P_i, \ldots, P_M\right) \tag{1}$$

where P_i is the value of ith pressure sensor and M is the number of pressure sensors.

7) Average pressure: The average pressure of all the sensors or in a specific area such as heel area or toe area.

$$P_{\text{ave}} = \frac{1}{M}\sum_{i=1}^{M} P_i. \tag{2}$$

8) COP location: The values of COP in both X- and Y-axes.

$$X_{\text{COP}} = \frac{\sum_{i=1}^{N} X_i P_i}{\sum_{i=1}^{N} P_i}, \quad Y_{\text{COP}} = \frac{\sum_{i=1}^{N} Y_i P_i}{\sum_{i=1}^{N} P_i} \tag{3}$$

where X_i and Y_i are the coordinate values for ith pressure sensor and N is the number of the sensors.

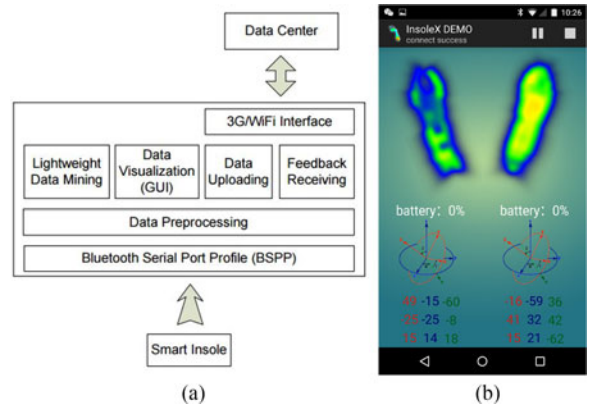


Fig. 5. Software of Smart Insole. (a) Stacked software structure. (b) Data visualization GUI on a smartphone software.

9) COP velocity: The moving speed of COP.

$$V_{\text{COP}} = \frac{1}{\Delta t}\begin{pmatrix} \left|X_{\text{COP}}\left(t+\Delta t\right) - X_{\text{COP}}\left(t\right)\right|^2 \\ +\left|Y_{\text{COP}}\left(t+\Delta t\right) - Y_{\text{COP}}\left(t\right)\right|^2 \end{pmatrix}^{1/2} \tag{4}$$

where Δt is the time interval.

2) Software Stacks and Visualization: The software system on the smartphone of Smart Insole consists of three stacked layers as shown in Fig. 5(a), which are the physical driver interface, data preprocessing module, and data postprocessing module. In order to perform the real-time computing, the software is implemented with multithreading technology. In general, there are six main threads in the software program. Specifically, a device driver thread handles asynchronous communication to Smart Insole over the Bluetooth serial port profile (BSPP). The device driver synchronizes the incoming sensor data before forwarding to the client programs over interconnect sockets. Another thread performs data preprocessing, including denoising of the collected pressure sensor data [15], calibrating inertial sensor values with filtering, and initializing the baseline with magnetometer data. After the aforementioned steps, the clean, compressive, and informative data are obtained. After that the following processing will be dispatched to the corresponding services on the next layer. The remaining four threads receive the preprocessed data, perform two local services, and two remote services, respectively. A GUI application on smartphone is developed to record, visualize, and analyze the data from Smart Insole, as shown in Fig. 5(b). We also built a GUI software on a computer as shown in Fig. 6. In this GUI, pressure maps under two feet are visualized. At the same time, the foot orientation is also displayed with the calibration motion sensor information.

IV. Evaluation

A. Experimental Setup

The purpose of this evaluation is to validate Smart Insole by collecting complete gait parameters and further extracting useful features. The experiments consist of a quantified study and a longitudinal study. The quantified study aims at providing a quantified measurement of the gait parameters and features,

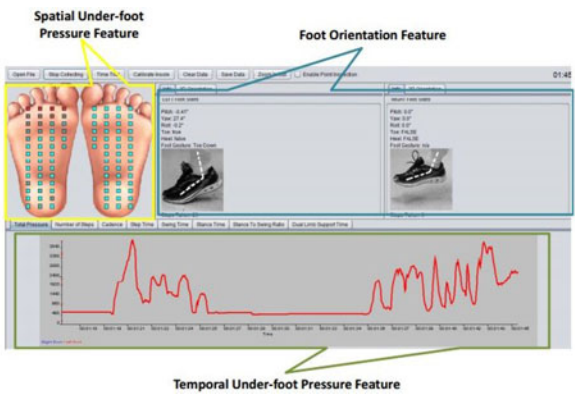


Fig. 6. Data visualization on a computer software.

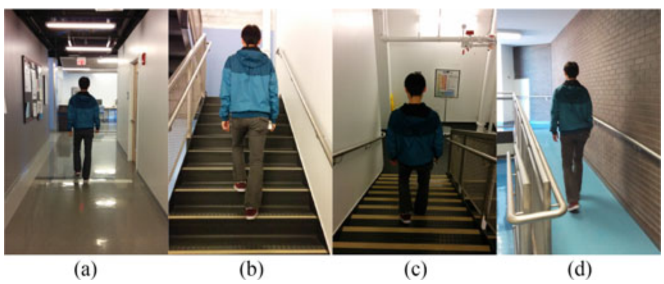


Fig. 7. Experimental scenes of walking. (a) Hallway walking. (b) Ascending stairs. (c) Descending stairs. (d) Slope walking.

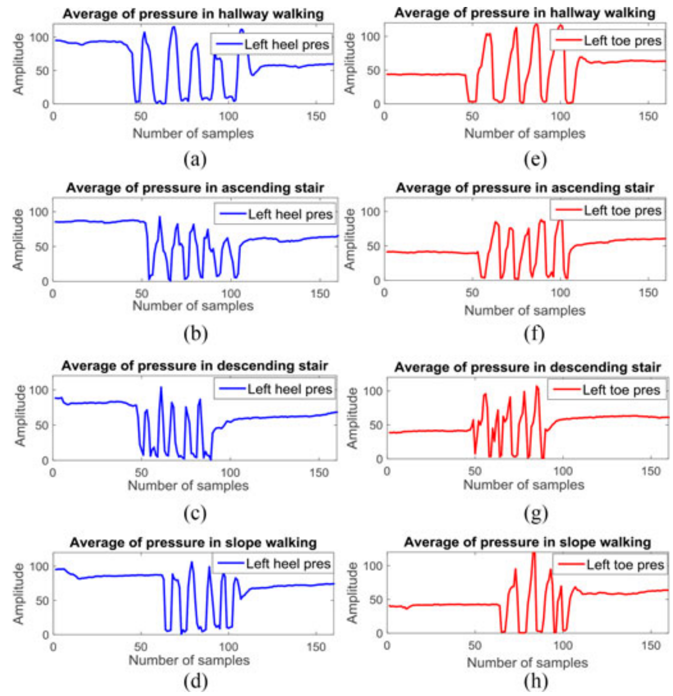


Fig. 8. Left plantar pressure from both heel and toe groups in different scenes. (a) Heel pressure in hallway walking. (b) Heel pressure in ascending stairs. (c) Heel pressure in descending stairs. (d) Heel pressure in slope walking. (e) Toe pressure in hallway walking. (f) Toe pressure in ascending stairs. (g) Toe pressure in descending stairs. (h) Toe pressure in slope walking.

while the longitudinal study tries to verify that Smart Insole is feasible and suitable for continuous daily life activities (DLA) monitoring. All the features discussed in the following have been introduced in Section III-C1. These features are meaningful in real life, such as pressure can be used for foot protection, step count and step pace for exercise monitoring, and COP for balance estimation. We evaluate Smart Insole across different sets of scenes, such as hallway walking, ascending stairs, descending stairs, and slope walking, as shown in Fig. 7. For the step count performance evaluation, we adopt a pedometer (OMRON HJ-720) fixed on the subject's waist as the ground truth reference. In all the evaluations, we intend to use "number of samples" in x-axis because it can emphasize the sampling rate/resolution is enough to characterize gait parameter during one gait cycle. In the data collection, the sampling frequency is set as 100 Hz, the sampling resolution is 12-bit, three channels for three MUXs, and the reference voltage is 3.3 V. Therefore, it is straightforward to convert x–y axis into the standard metric unit, i.e., time, voltage, and distance.

B. Quantified Study

1) Pressure Analysis: In pressure analysis, we are interested in both regional pressure such as toe or heel area, and overall pressure. The pressure data collected from the insole can be utilized to identify the phase of gait, which leads to further gait features calculation such as the step count and step pace. The first step of the phase identification is to detect the heel strike and toe-off instants during a gait cycle. To this end, pressure sensors around the toe area and around the heel area are grouped, respectively, for further data processing. The toe group includes sensor indexes from 1 to 5. The heel group includes sensor indexes from 43 to 48. The order of the indexes begins from inner to outer and from top to down. The average and maximal pressures are calculated based on each group. The raw pressure data in different evaluation scenes from both heel group and toe group are shown in Fig. 8. Since the data obtained from the left foot and right foot exhibit similar patterns, we only provide the data from the left foot for simplicity. We notice that the average pressure and duration of gait cycle of the subject are slightly different when the subject is performing in different walking scenes, which is because he did not walk exactly at the same speed in the experiments.

2) Steps: In gait analysis, how many steps a subject walks and how fast the subject walks are two important features. Both the toe group and the heel group pressure data can be used to calculate the step count and step pace, because these areas contain the most informative data, such as heel strike and toe-off moments, during walking. The average of the pressure within each group is adopted as representative of pressure distribution for the step count and step pace calculation. The numeric derivatives of pressure are calculated for the heel strikes and toe-off activities detection, which are robust against the spurious signals, different offset of the insoles, and different weights of subjects. In a gait cycle, once a derivative value of heel area exceeds the threshold, which is presetted as 25 times of the

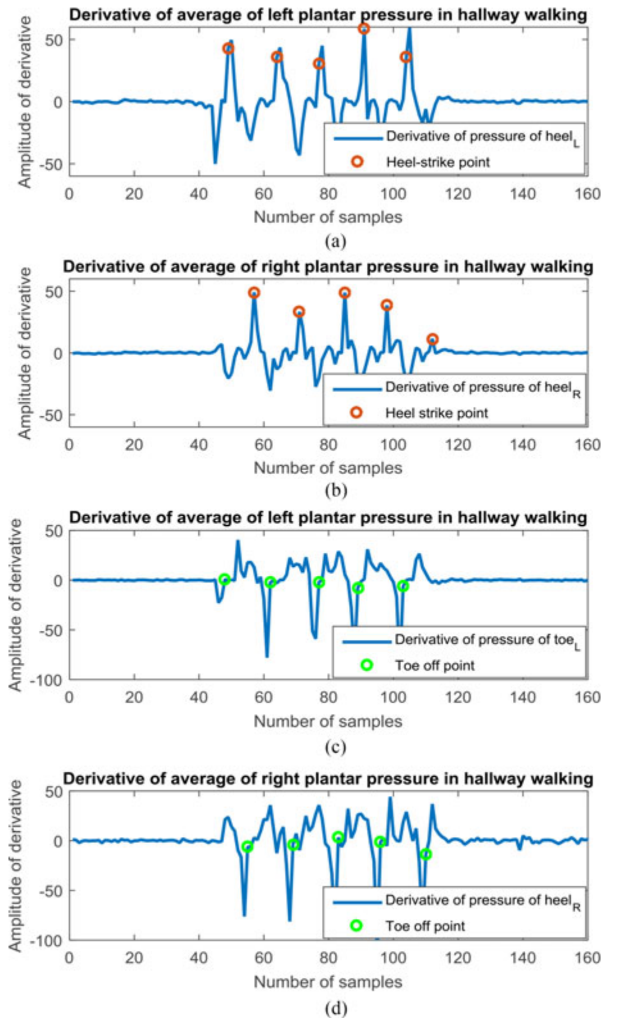


Fig. 9. Derivative of plantar pressure from both feet. (a) Left heel strike. (b) Right heel strike. (c) Left toe-off. (d) Right toe-off.

standard deviation of the derivative pressure of the quiet stance, the critical point indicates a heel strike happens. Similarly, when a derivative value of toe area exceeds (in the toe area case, exceed actually means smaller than) the negative threshold with the same definition of the heel area case, the critical point indicates a toe-off activity. Fig. 9 shows the derivative data from both heel and toe areas of both feet in a hallway walking process. The heel strike and toe-off points are marked as red and green circles, respectively.

We notice that in Fig. 9(b) the last peak of the right foot is not as prominent as the other peaks. The reason of such phenomenon is because the last peak indicates the last stop step. The subject initiated the walk with the left foot and ended up with the right foot. In the last stop step, he moved his right leg close to the left leg to stop walking instead of stepping forward, which results only a slight heel pressure change of right foot compared with the normal stepping forward. Similarly, the first small peak in Fig. 9(c) is caused by the initial toe-off of the first step. Due to the phenomena described, we consider the heel strike of start foot and toe-off of end foot are more robust than the other two features for calculating the step count.

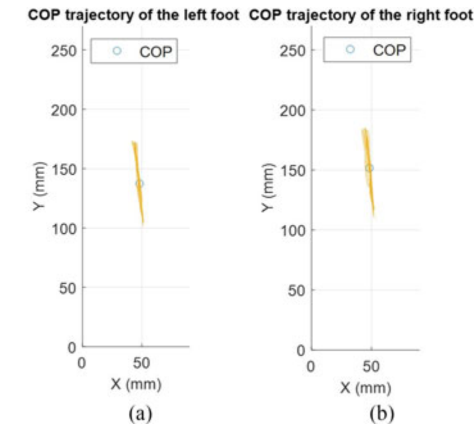


Fig. 10. Trajectories of COP shifting in hallway walking. (a) Left foot. (b) Right foot.

TABLE III
GAIT FEATURE PARAMETERS IN HALLWAY WALKING

	Left Foot	Right Foot
Step count	5	5
Step pace (steps/min)	34	34
Average swing time (s)	0.486	0.542
Average stance time (s)	1.45	1.36
Average duration of gait cycle (s)	1.936	1.904
Maximal COP velocity (mm/s)	187.75	174.62
Average COP velocity (mm/s)	13.69	10.54

As the step count is equivalent to the number of heel strikes or toe-offs because one step contains only one heel strike and one toe-off, the step count can be identified automatically by calculating the number of the left heel strikes or right toe-offs. In generally, it can be summarized as

$$\#\,(\text{steps}) = \#\,(\text{initial foot heel strikes})\ \text{ or } \#\,(\text{end foot toe-offs}) \tag{5}$$

where # means the number of. After that, the step pace can be easily obtained by calculating how many steps walked in one minute.

3) Balance: The COP location and COP shifting speed are important metrics for evaluating walking balance. When the COP shifting speed exceeds a certain threshold, it indicates the walker is in a unstable walking status, which may imply an early symptom of some neurological diseases. The trajectories of the COP shifting in a hallway walking are shown in Fig. 10. The length of *X*-axis is 90 mm and the length of *Y*-axis is 270 mm, which are just the width and length of Smart Insole. The yellow traces represent the trajectories of the COP shifting, from where we can see the COPs of both feet shifting back and forth around the central area, and the subject is slightly prone to left when walking in the hallway. The blues circles indicate the final COP location when the subject stops, i.e., the subject stands still with two feet supporting the whole body. The maximal distance that the COP traveled away from the COP location in stance status is about 40 mm, which suggests a stable walking. The rest aforementioned gait features in hallway

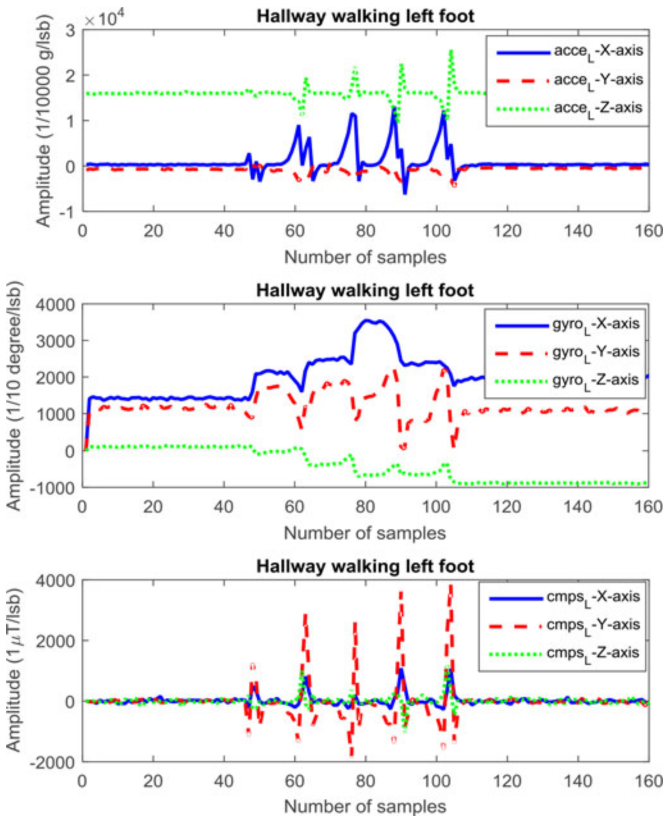


Fig. 11. IMU data from left foot in a hallway walking, from top to bottom are accelerometer, gyroscope, and magnetometer data.

walking are summarized in Table III. The pedometer shows five steps as well.

4) Inertial Measurement: The IMU data from left insole including the data from accelerometer, gyroscope, and magnetometer are shown in Fig. 11. Because of the page limit, we only show left insole data here. Among these curves, the accelerometer data in X -axis and Z -axis are most relevant to the hallway walking activity, where X-axis data represent the anterior–posterior movement, Y-axis data represent the medial-lateral movement, and the Z-axis data represent the vertical movement.

C. Real-Case Study

We performed a pilot study in a complex real-world scenario to verify the feasibility of Smart Insole in the DLA monitoring. The DLA is divided into seven activity segments including initial sit down and keep sitting, walk to stairs, descend stairs, run, ascend stairs, walk to seat, and final sit down and keep sitting, which are typical scenes in life. The panorama of the continuous DLA is shown in Fig. 12. The subject performed these activities in sequence in real word is shown in Fig. 13. The average and maximal pressure are obtained from this longitudinal experiment and are depicted in Fig. 14(a) and (b), respectively. The pressure waveform density in each segment implies the step pace. We notice that the pressure waveform from run are denser and the pressure from ascend stairs are sparser comparing with the pressure from walk and descend stairs, though they are not

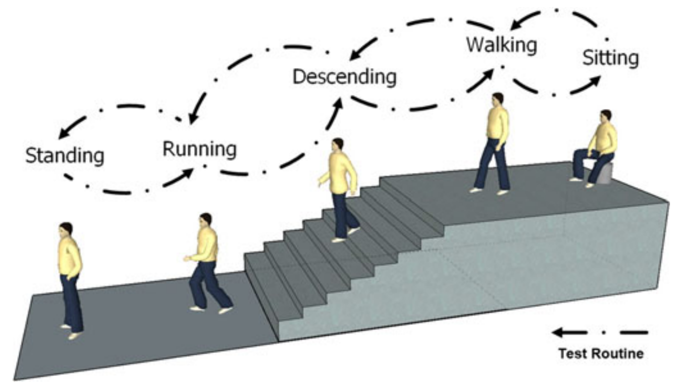


Fig. 12. Panorama of the continuous DLA.

so apparent. In Fig. 14(b), the maximal pressure in the two walking activities differentiates with each other, which suggests the subject walked differently. Similarly, the different maximal pressure between two sittings is because of the sitting postures, with more weight load put on the foot in the end sitting than in the initial sitting. The average step pace during each activity is calculated and shown in Fig. 15, and is in accordance with the density difference observed in Fig. 14. In all these DLAs, Smart Insole shows the same step count result with the results from pedometer and human observation. we also conducted a comparison study of Smart Insole on real-world step count compared with wrist band (Mi Band) and smartphone that is reported in another work [19]. In that work, 10 healthy subjects took 19 tasks in the experiment to prove the robustness of Smart Insole. Each subject took 100 steps in each task, which means 19 000 steps imposed on Smart Insole during the test. The 19 evaluation tasks includes straight line walking with four arm postures, twisted route walking with four arm postures, fast walking, backward walking, jogging, running, sprinting, backward running, ascending stairs, descending stairs, walking with cane, ascending stairs with cane, and descending stairs with cane. We did not observe any data transmission problem or sensor failure problem during this experiment. The evaluation results with statistical accuracy of more than 99% in step count proves the robustness and reliability of Smart Insole.

V. Discussion

A. Limitation and Improvement

1) Promote the Usability of Smart Insole With Wireless Charging: Many older adults gave us feedback that they are handicapped with mini-USB charger in Smart Insole, so the wireless charging function is necessarily needed. Wireless charging also known as inductive charging is a method of moving power wirelessly. A power generating source system is placed near a power storing or power transferring system. An electromagnetic field is generated between the two objects and power is moved from one system to the other. Wireless charging technology becomes mature in recent years. Several available commercial products dedicated for wireless smartphone charging functionality, such as PowerMat 3X, Energizer Inductive

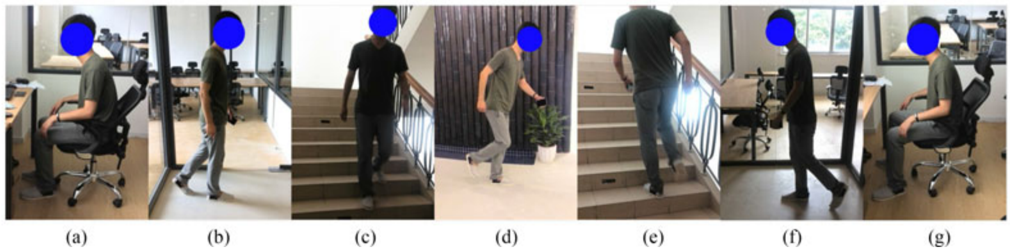


Fig. 13. Continuous experimental scenes of the DLA in real-world setting. (a) Sit down and keep sitting. (b) Walk to stairs. (c) Descend stairs. (d) Run. (e) Ascend stairs. (f) Walk to seat. (g) Sit down and keep sitting.

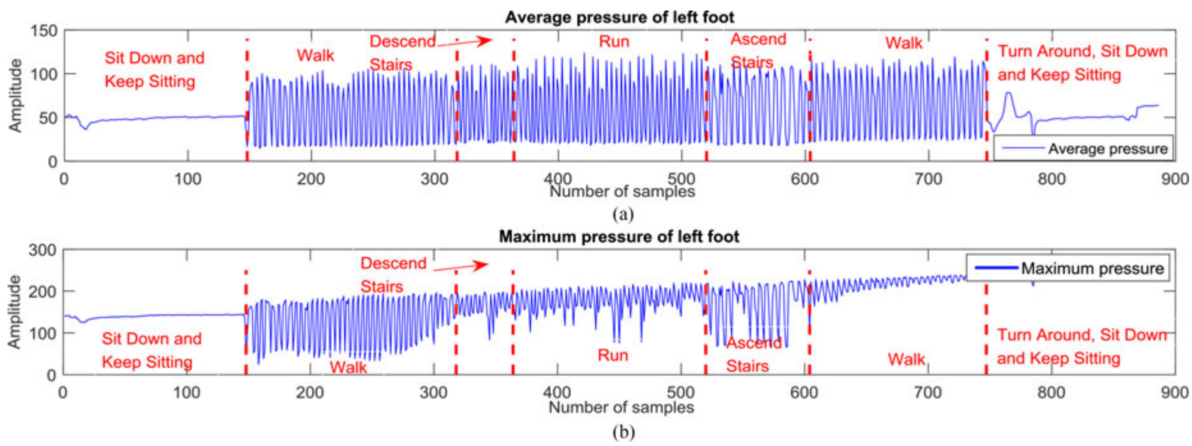


Fig. 14. Pressure of left foot in daily life activities. (a) Average pressure. (b) Maximal pressure.

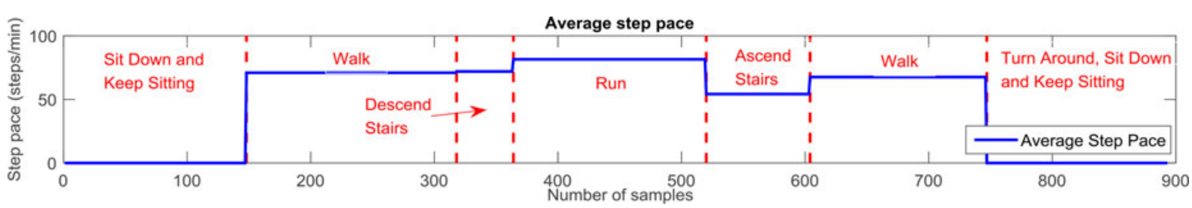


Fig. 15. Average step pace in daily life activities.

Charger, and Duracell MyGrid. Recent progress in wireless charging [20], [21] can transmit energy with low transmitter voltage while without precise coil alignment, and the receiving coil can be made very small. Nevertheless, integrating magnetic resonance coupling circuit into Smart Insole is still challenging. This is because all circuit components placed inside the insole are constantly under the pressure caused from human weight. Electronics and sensors can be damaged easily without appropriate displacement and packaging methods. Fortunately, our team has considerable experience with the circuit design and integration in the insole. We will perform an end-to-end usability evaluation in the future.

2) Global Positioning System (GPS) Module Integration for Position Tracking: Geographical location of older adults during daily life activities provides necessary information to assess the impact of environmental exposure for older adults' health and locate the positions of old adults who got lost. In the current prototype, GPS module is not provided. In our future plan, Smart Insole will be developed into different models. One of the models will be equipped with a GPS, mainly targets the groups of old adults with Alzheimers, dementia, Autism, or other cognitive disorders and people who need location information. Old adults with those diseases are prone to get lost, Smart Insole with GPS is able to track and report the real-time position information of patients. One challenging in implanting a GPS into the device is restricting the device within the set weight since GPS will be part of multisensors. Other models will exclude GPS module to maintain a low computational complexity and energy consumption. Shoes integrated with GPS have been developed for people with Alzheimers, dementia, Autism, or other cognitive disorders [22], but GPS is the only device built in those shoes.

B. Wearability and Usability

Two older adults have used Smart Insole for the wearability test. They walked wearing Smart Insole in disparate environments, including indoor/outdoor, ascending/descending stairs, flat ground/slope, hard ground/soft ground, and with/without walker. We provided Likert scale and open-ended questions to ask about the wearability and usability satisfaction (e.g., ease/difficulty in operating the device, readability of the figures on smartphone, preference for weight, size, and color). The two participants were satisfied with Smart Insole. In the future, we will test Smart Insole with a larger cohort.

Comparing with Smart Insole, existing products lack usability because of two reasons. First, they are too expensive for in-home use. For example, the plantar pressure measurement platform by Zebris starts at about $16 000, while Pedar by Novel [13] costs $14 850. Second, these devices are bulky, inconvenient, and can potentially alter foot-pressure patterns when in use. Furthermore, these systems may require a potentially unsafe control unit that is obtrusive to the user and could lead to injuries in daily use. Other lightweight solutions such as Fitbit, Garmin, and Nike Band only provide limited activity information (walking step, distance, etc.) rather than profiling detailed gait parameters.

C. Future Work

1) Optimize and Extend the Battery Life: The battery lifetime is a key concern in the real-life application. We will further explore the energy-efficient sensing and computing technologies to extend the battery lifetime. Our potential method is based on adaptive compressed sensing [23]. Specifically, we are going to develop a context-aware sensing scheme for human activity and gait analysis. Human gait can be divided into a set of different stages. This scheme can sense different gait styles and adaptively control the sampling density and locality. There are three steps in this sampling scheme, i.e., the presampling for stage recognition, local randomized selective sensing, and sparsity-based reconstruction. We will implement this approach on the unmodified ADC, and integrated with the current insole prototype. With one 1200-mA.h Li-battery, the system can continuously work for more than 24 h. Therefore, this Smart Insole system can be used daily without interruption because of charging the battery.

2) Develop a Robust Computational Model to Estimate Energy Expenditure: The current Smart Insole can calculate physical intensity (e.g., step count and step pace) with an array of integrated sensors (pressure, accelerometer, gyroscope, and magnetometer), and recognize motion activities with a corecognition model. We plan to develop a robust computational model to enhance and automate the calculation of energy expenditure by leveraging the obtained activity information. Specifically, this model can transfer physical intensity and activity to the metabolic equivalent of task, which is then used to approximate the calories burned.

3) Conduct a Thorough Evaluation Study in a Standard Gait Laboratory: This study mainly focuses on the design of Smart Insole. In our future work, in addition to real-world step count performance evaluation in [19], we plan to conduct a thorough evaluation study using Smart Insole in a standard gait laboratory with more people and quantitatively examine the accuracy of other gait parameters, such as COP, stride length, etc.

D. Healthcare-Related Potential Applications

Taking advantage of the affordability and mobility of Smart Insole, pervasive gait analysis can be extended to many healthcare-related potential applications, such as fall monitoring, injuries prevention, life behavior analysis, and networked wireless health systems.

1) Fall Monitoring in Older Adults: One in three adults aged 65 or older falls each year. In 2013, the total medical cost due to falls has reached 34 billion dollars in United States [24]. Fall and fall-induced injuries among the elderly population are a major cause of morbidity, disability, and increased healthcare utilization [25]. Among scientific geriatric studies, fall prevention is probably the most studied subject using technology. The challenge for fall detection is to create a highly accurate, unobtrusive device that is tested in a real life situation. With our developed Smart Insole, geriatric researchers will be able to detect when and how falls occur in older adults at risk. The study will not be limited in a gait laboratory, instead, it could be in any scenes in real life, such as indoor walking, outdoor exercises, climbing hills, ascending/descending stairs, etc.

2) Prevention of Work-Related Injuries: Construction industry has the highest count of slips, trips, and falls (STF) related fatalities in United States. Many countries are facing the same challenges with STF injury problems in the workspace. STF incidents, resulting from multifactorial, encompassing human, environmental, and task risk factors, even homes, and communities. Smart Insole can significantly enhance occupational security and health in construction industry, wholesale, and retail trades workspaces through providing real-time and continuous sensory surveillance, risk factors identification, effective and just-in-time intervention methods.

VI. Conclusion

In this paper, a novel wearable sensor device for unobtrusive gait monitoring called Smart Insole has been proposed. The device is based on integrated textile pressure sensor array and IMU sensor, offering complete gait parameters acquisition. Visualization software has been developed for gait monitoring on smartphone. Furthermore, the device is comfortable to wear, convenient to use, and cost effective, which makes it suitable for various healthcare applications and daily life usage.

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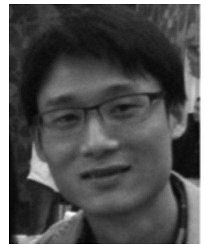

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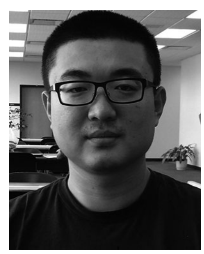

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