

A Comparative Study of Smart Insole on Real-world Step Count

Feng Lin, Aosen Wang, Chen Song, Wenyao Xu

Department of Computer Science and Engineering

University at Buffalo, SUNY

Buffalo, New York 14260-1660

Email: {flin28, aosenwan, csong5, wenyaoxu}@buffalo.edu

Zhinan Li, Qin Li

Shenzhen Chuanggan Technology (Sennotech)

Shenzhen, China 518057

Email: {lizhinan, liqin}@sennotech.com

Abstract—Daily step count is an important parameter in energy expenditure estimation, medical treatment, and rehabilitation. However, traditional step count methods are not user-friendly or require adhesive equipment. In this paper, we present our Smart Insole system design and evaluate its step count performance. Smart Insole is lightweight, thin, and convenient to use, providing an unobtrusive way to perform step counting. The Smart Insole step count method is based on the differential value threshold of the average plantar pressure obtained from the ambulatory gait assessment. We perform a set of real-world experiments considering different arm positions, walking styles, and daily life activities to evaluate the step count performance. The results show Smart Insole can achieve nearly 100% accuracy in step count under various circumstances, which outperforms other existing solutions.

I. INTRODUCTION

Daily step count is one of the most used parameters to estimate energy expenditure in daily life activities. Correct energy expenditure estimation can help guide the rehabilitation of metabolic syndrome, such as coronary heart disease [1], diabetes [2], and stroke [3]. The results from step count also have a considerable amount of applications in physical therapy, and exercise training [4]–[6]. For example, step count within a certain time, namely, step frequency, is an important measurement index in the timed up and go test system [7], where a subject is required to walk back and forth within a specific amount of time to determine fall risk and measure balance.

In recent years, it has been intensively investigated how to accurately estimate daily step count. Prevailing clinical practice for evaluating step count is based on subjective clinical observation. An observer watches a subject's activity and count how many steps that he took. One popular alternative approach to measure step count is to use video camera recording, which requires the subject to be confined in a camera surveillance area. Android-based smartphones [8] have integrated step detector and step counter sensors to track the steps. However, accuracy may be limited because the smartphone is not typically mounted securely. Wearable devices are also widely used for step count [9]. The data acquired from integrated inertial measurement unit (IMU) sensors can provide step evaluation. A pedometer [10] [11] is an example of this type of step-count device. Many off-the-

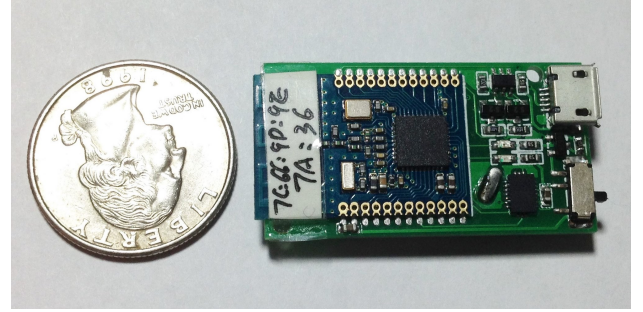


Fig. 2. The PCB design of the control system in Smart Insole and size comparison with a quarter dollar.

shelf products designed for the wrist have been developed, including Mi Band [12], Fitbit [13], and Apple Watch [14]. The StepWatch step activity monitor [15] is another dual axis accelerometer device mounted on the shank. However, these wearable devices require the user to adhere to mounting them on the waist or shank, which may be uncomfortable and inconvenient.

In this paper, we propose using Smart Insole to obtain an accurate step count in the real world. Smart Insole looks and feels like an insole and is convenient to use in daily life. It consists of an array of pressure and IMU sensors, an ultra-low power micro control unit (MCU) and Bluetooth low energy (BLE) wireless transmission module, a channel multiplexer (MUX), a Li-battery, and a micro-Universal Serial Bus (USB) connector module. We primarily focus on the evaluation of the real-world step count performance of Smart Insole, the step count method is based on the differential value threshold of the average plantar pressure obtained from the ambulatory gait assessment. We perform a set of step count evaluations in a real-world environment considering different arm positions, walking styles, and daily life activities. Our results indicate nearly 100% accuracy in measuring step count..

The organization of the remaining paper is as follows: In Section II, we describe the Smart Insole system, including system overview, textile pressure array, inertial motion sensors, MCU and BLE, battery and micro-USB connector, and ergonomic design. In Section III, a simple step count algorithm

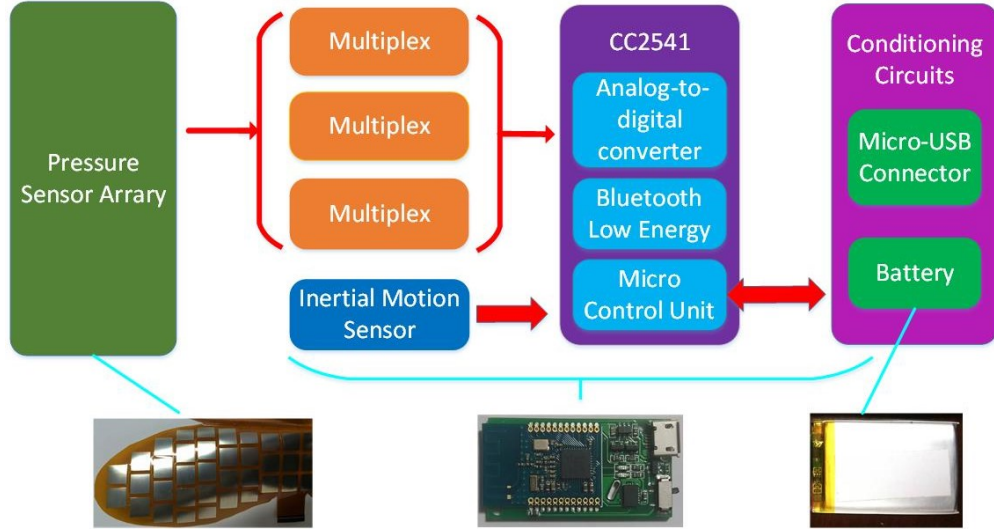


Fig. 1. The overall architecture design for Smart Insole and pictures for each component.

is described. Section IV provides the evaluation of step count in a real-world environment. Finally, the paper is concluded in Section V.

II. SMART INSOLE

A. System Overview

The goal of Smart Insole is to accurately and consistently capture the complete gait parameters. It is also designed to be comfortable to wear and convenient to use. The overall architecture design is shown in Fig. 1. Smart Insole includes 1) textile pressure sensor array, 2) the MCU and BLE module, 3) the 9-axis inertial motion sensor, 4) the micro-USB connector, 5) the battery module. The printed circuit board (PCB) design of the control system is shown in Fig. 2.

B. Textile Pressure Array

The textile pressure sensor array [16] [17] is used to obtain the high-resolution pressure map under feet. It is based on an advanced conductive textile fabric sensor technique and can be efficiently integrated with Smart Insole system. There are 48 pressure sensors embedded in the insole, each one of which is a square pressure sensor as shown in Fig. 3. The diagram of the driving circuit is depicted in Fig. 4. The output of pressure sensors is chosen by three 16 to 1 channel MUXs (ADG706 from Analog Device) to connect to the analog-to-digital converter (ADC) input of the micro-controller.

C. 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 [18] in the Smart Insole system, which integrates a 12-bit accelerometer, a 16-bit gyroscope, and a magnetometer



Fig. 3. The real pressure sensor array design and wire connection.

in a single chip. Accelerometer, gyroscope, and magnetometer data in X, Y, and Z axes are sampled simultaneously.

D. Micro Control Unit and Bluetooth

The MCU and Bluetooth are implemented by a single device CC2541 [19]. The CC2541 combines a radio frequency (RF) transceiver with an enhanced 8051 MCU, a 256kB in-system programmable flash memory, an 8kB random-access memory (RAM), a 12-bit $\Delta - \Sigma$ mode ADC, and a hardware I2C bus. The sensor data from 3 MUXs are digitalized by 8-channel, 12-bit, and 0-3.3 volt ADC module. The sampling rate can be adaptive for specific applications, up to 100 samples per second (Hz).

E. Battery and Micro-USB Connector

The battery module contains a battery connector, a 3.3V 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 the 9-axis inertial sensor and channel MUXs. The micro-USB connector is used for charging the battery, programming CC2541, and online debugging.

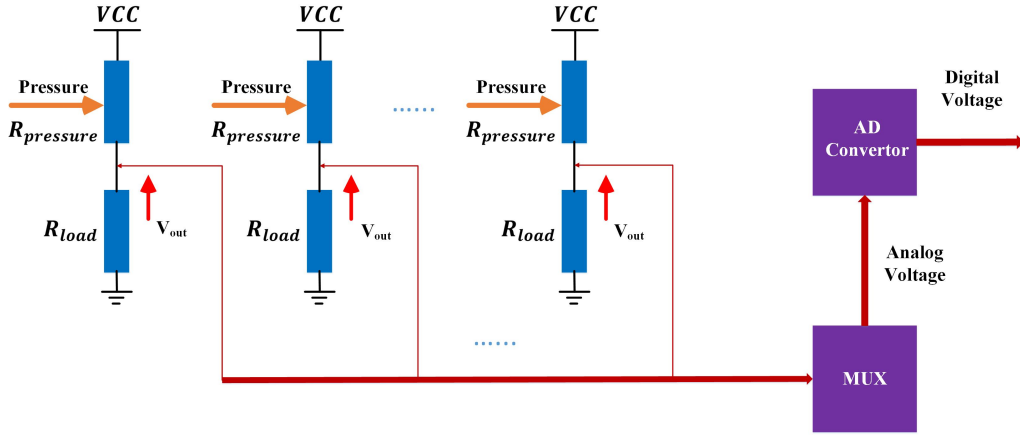


Fig. 4. The circuit level design of pressure sensor array of Smart Insole.



Fig. 5. The human ergonomic prototype of Smart Insole.

F. Package and Ergonomic Design

Smart Insole is lightweight (< 2 oz.), thin, convenient to use, does not need calibration, and only requires minimal setup procedures. The prototype of Smart Insole is shown in Fig. 5. Smart Insole is similar to a normal insole without any extra cable, antenna, or adhesive equipment.

III. STEP COUNT ALGORITHM DESIGN

Smart Insole is capable of offering an accurate step count based on simple threshold settings. With the conductive textile fabric pressure array, the pressure data from the 48 sensors can be obtained. In the step count algorithm, we are interested in the average pressure of all the sensors, defined as:

$$P_{\text{ave}}(t) = \frac{1}{N} \sum_{i=1}^N P_i(t), \quad (1)$$

where P_i is the value of i th pressure sensor and N is the number of pressure sensors, i.e., 48.

The differential of average pressure is calculated as:

$$P_{\text{diff}}(t) = \frac{dP_{\text{ave}}(t)}{dt}, \quad (2)$$

The differential of average pressure data waveform generated from continuous walking is shown in Fig. 6 (a), which

is robust against the spurious signals, different offset of the insoles, and different weights of subjects [20]. As human gait is a repetitive motion, time series of gait signals are pseudo-periodic in nature. A pair of peak and valley waveforms corresponds to a step walk event, so the step count is equivalent to the number of peaks in the waveform. As a result, we aim at determining how many peaks appear in the average pressure data. The main idea is to detect a positive edge and the following negative edge, which together account for one peak. To achieve this goal, we set a high threshold Γ and a low threshold γ in advance, the values of which are based on empirical data. The valid empirical threshold range is between 10 and 40. When the pressure value exceeds the high threshold, it indicates a positive edge. Likewise, when the pressure value is less than the low threshold, it indicates a negative edge. The diagram of the peak detection is depicted in Fig. 6 (b). After the peak is detected, the step count can be easily obtained by calculating the number of peaks. The whole procedure of step count is summarized in Algorithm 1.

Algorithm 1 A simple step count algorithm with double thresholds

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1: Input:  $N$  channels pressure  $P_i(t)$ ,  $1 \leq i \leq N$ .
2: Preset  $\Gamma$  and  $\gamma$ ;
3: Calculate the average pressure  $P_{\text{ave}}(t)$ ;
4: Calculate the differential of average pressure  $P_{\text{diff}}(t)$ ;
5: Initial: status = 0, step count = 0;
6: while 1 do
7:   if  $P_{\text{diff}} < \gamma$  then
8:     if status = 1 then
9:       step count = step count + 1;
10:    end if
11:    status = -1;
12:  else if  $P_{\text{diff}} > \Gamma$  then
13:    status = 1;
14:  end if
15: end while
16: Return: step count.

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The algorithm is simple, straight forward, and effective with low-complexity computing. There are two reasons that we did not pursue a more advanced algorithm. First, the computational capability in wearable devices is limited, which requires low-complexity computing. Second, the current algorithm has shown satisfactory performance in step counting under various conditions. The evaluation results are presented in Section IV.

IV. EVALUATION

A. Experimental Setup

To evaluate the step count performance of Smart Insole, we provide a set of walking styles and daily activities tests for assessing gait. The Mi Band is selected as the benchmark for comparison, which is mounted on the left wrist of the subject during the test as shown in Fig. 7 (a). There are two sets of experiments. First, we perform a study concerning the impacts of different arm positions for Mi Band and walking styles for Smart Insole in a normal walking event. Second, we conduct a daily life activities (DLA) study, which focus on the robustness of Smart Insole in a realistic living environment. The high and low thresholds in this experiment are chosen as 30 and 20, respectively. Ten healthy subjects, including seven males and three females, participated in the experiment. In this work, we focus on the evaluation using healthy people with no leg or foot problems. The weights of all participants are from 45 to 87 kg and heights from 157 to 185 cm. Each subject walked 100 steps in each test scenario. The results shown below are the average values of all the subjects.

Accuracy is adopted to quantify the step counting performance, which is defined as:

$$\text{Accuracy} = \left(1 - \frac{|N_{true} - N_{cout}|}{N_{true}}\right) \times 100\%, \quad (3)$$

where N_{true} and N_{cout} are the number of true steps and counted steps, respectively.

B. Study with Different Arm Positions and Walking Styles

In this study, the subject walk on a flat ground with normal speed as shown in Fig. 7 (b). As Mi Band is mounted on the wrist of the subject, how the upper extremities behave in walking may have an impact on the performance of Mi Band. Thus, we designed four scenarios for the arms and hands' placement. Specifically, they are arms swinging naturally, arms folding over chest, operating cellphone in front of chest, and hands in pant pockets. We also considered two walking styles, including walking in a straight line and walking irregularly in a twisted route. The step count results are summarized in Table. I, where the average accuracies of Smart Insole and Mi Band are 100% and 98.6%, respectively. Both Smart Insole and Mi Band achieve high accuracies in walking step count; however, Smart Insole performs better than Mi Band in almost all circumstances. In addition, we noticed that the results obtained across different arm positions and walking styles remain the same for Smart Insole and show little difference for Mi Band, which proves both systems, especially Smart Insole, are robust against the changes in the aforementioned scenarios.

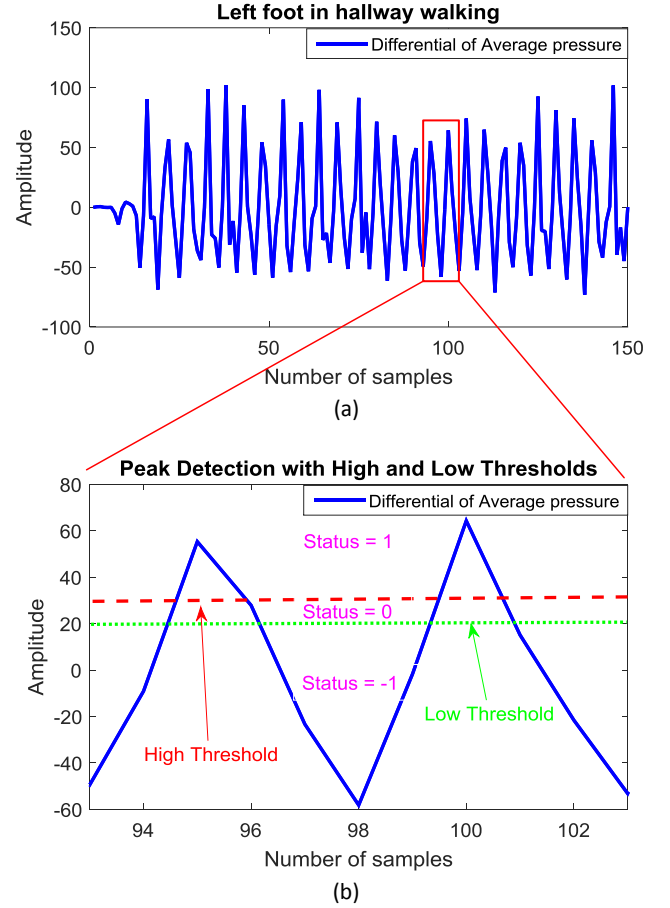


Fig. 6. Pressure data from left foot walking on flat ground: (a) The differential of average pressure of all sensors. (b) The diagram of peak detection with double thresholds.

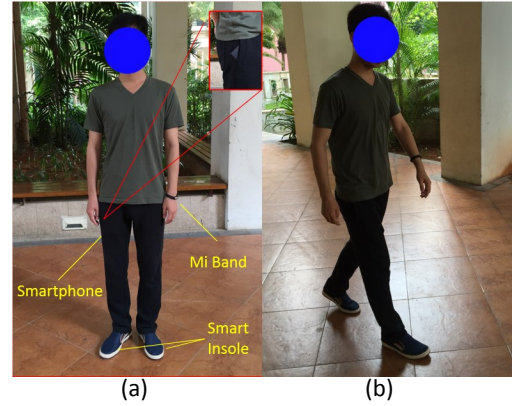


Fig. 7. Evaluation setting and scenario: (a) Sensor. (b) Normal walking scene.

C. Study with Daily Life Activities

The study with DLA focuses on verifying Smart Insole is suitable for step count used in daily life. A smartphone with a step counting application is also adopted for comparison in ad-

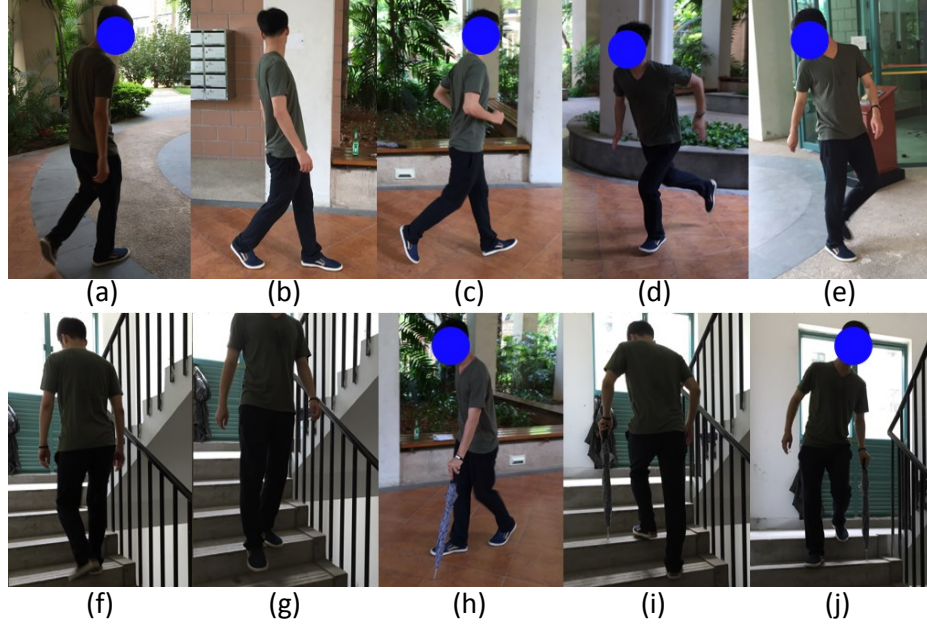


Fig. 8. DLA designated in the evaluation: (a) Fast walking. (b) Backward walking. (c) Jogging and running. (D) Sprinting. (e) Backward running. (f) Ascending stairs. (g) Descending stairs. (h) Walking with cane. (i) Ascending stairs with cane. (j) Descending stairs with cane.

TABLE I
STEP COUNT WITH DIFFERENT ARM POSITIONS AND WALKING STYLES

Route	Arms & Hands	Smart Insole	Mi Band
Straight line	Swinging naturally	100	97.8
Straight line	Folding over chest	100	102.1
Straight line	Operating cellphone	100	100.8
Straight line	Hands in pockets	100	101.3
Twisted route	Swinging naturally	100	100.9
Twisted route	Folding over chest	100	101.5
Twisted route	Operating cellphone	100	100.3
Twisted route	Hands in pockets	100	102.1

dition to Mi Band, which is put in the right pant pocket. There are 11 designated activities, as shown in Fig. 8, including 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. The arms are required to swing naturally except when the subject uses a cane, which emulates the elderly walking with the help of a cane. The step count results are summarized in Table II and the bar graph is shown in Fig. 9. The red line in Fig. 9 indicates the actual step count value. The indexes in the figure are the same as the ones in Table II. When the subject uses a cane, Mi Band failed to detect the ascending/descending stair activities because the wrist movement is slow and subtle in these cases. Walking with a cane from Mi Band also shows an inaccurate step count result, which failed to detect more than half of the steps. However, Smart Insole still achieves 100% accuracy in all the activities because it directly uses the gait and pressure information rather

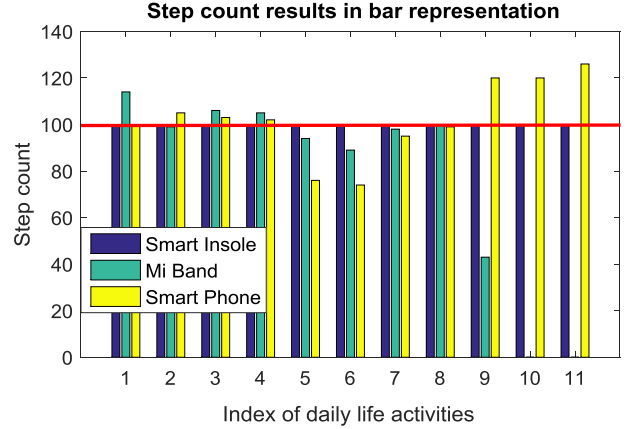


Fig. 9. Step count in bar graph for different DLA.

than the inferred upper extremities movement information. The accuracy comparison among Smart Insole, Mi Band, and Smartphone with all the DLAs is shown in Fig. 10.

V. CONCLUSION

In this paper, we propose a Smart Insole design and evaluate its performance on a real-world step count. Smart Insole is based on integrated textile pressure sensor array and an IMU sensor, offering complete gait parameters acquisition and satisfactory usability. We conducted a set of real-world experiments, including different walking route, arm position, and activities. The evaluation results demonstrated the system

TABLE II
STEP COUNT WITH DIFFERENT DLA

	DLA	Smart Insole	Smart Insole Accuracy	Mi Band	Mi Band Accuracy	Smartphone	Smartphone Accuracy
1	Fast walking	100	100%	114.6	85.4%	100.3	99.7%
2	Backward walking	100	100%	99.3	99.3%	105.7	94.3%
3	Jogging	100	100%	105.7	94.3%	103.2	96.8%
4	Running	100	100%	104.3	95.7%	102.9	97.1%
5	Sprinting	100	100%	94.1	94.1%	77.4	77.4%
6	Backward running	100.1	99.9%	89.2	89.2%	74.1	74.1%
7	Ascending stairs	100	100%	98.8	98.8%	96.5	96.5%
8	Descending stairs	100	100%	100.2	99.8%	99.0	99.0%
9	Walking with cane	100	100%	46.6	46.6%	119.2	80.8%
10	Ascending with cane	100	100%	0	0%	118.3	81.7%
11	Descending with cane	99.9	99.9%	0	0%	125.8	74.2%

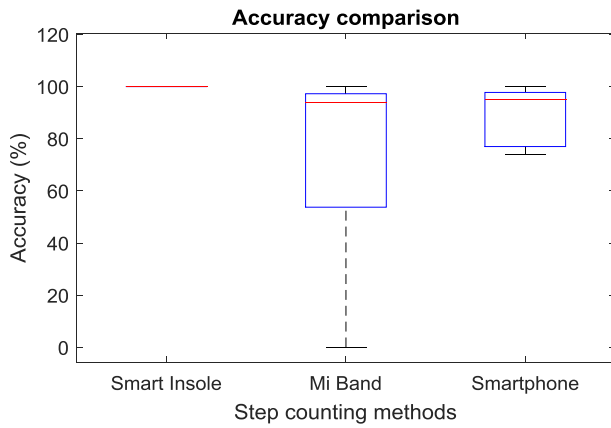


Fig. 10. Accuracy comparison among Smart Insole, Mi Band, and Smartphone with all the DLAs.

has the ability to count nearly 100% of the steps under various conditions, which outperform the existing commercial step count products.

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