FootNote: Designing a Cost Effective Plantar Pressure Monitoring System for Diabetic Foot Ulcer Prevention

Kin Fuai Yong, Juan Pablo Forero, Shaohui Foong, Suranga Nanayakkara*
Singapore University of Technology and Design (SUTD)
8 Somapah Road Singapore 487372.
*(corresponding author) : Suranga@sutd.edu.sg

ABSTRACT
Diabetic Food Ulcer (DFU) is one of the dangerous complications of Diabetes Mellitus that is notoriously progressive and high in recurrence. Peripheral neuropathy, or damage to nerves in the foot, is the culprit that leads to DFU. Many research and commercial development has attempted to mitigate the condition by establishing an artificial feedback through in-shoe pressure-sensing solutions for patients. However these solutions suffer from inherent issues of analog sensors, prohibitive price tags and inflexibility in the choice of footwear. We approached these problems by designing a prototype with fabric digital sensors. The data showed promising potential for assertion frequency tracking and user activity recognition. Although the bigger challenge lies ahead – to correlate approximation by digital sensors to analog pressure reading, we have demonstrated that an inexpensive, more versatile and flexible solution based from digital sensors for DFU prevention is indeed feasible.

Author Keywords
Wearable; Diabetic management; Peripheral Neuropathy; Diabetic Foot Ulcer; Podiatry.

ACM Classification Keywords
H.5.m. Information Interface and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION
Diabetes Mellitus stood as one of the most prevalent diseases with an estimated total of 347 million patients worldwide [1]. Patients' unmanaged blood sugar level will gradually damage their blood vessels and nerves. In its severe form, patients may not be able to feel any sensation from their peripherals, more commonly observed in lower extremities, i.e. feet. In many instances, unaware patients inflicted wounds under their feet due to trauma or excessive pressure. As the existing Diabetic condition slows the healing, the wound is highly susceptible to ulceration and subsequently infection and tissue necrosis. Such ulceration originated from Diabetic condition is called Diabetic Foot Ulcer (DFU). If left unattended, DFU could progress to bone infection where amputation is necessitated. Recent statistics in 2006 showed DFU is the cause of 65,700 non-traumatic lower limb amputations in US [2]. Wearable artificial sensors can rudimentarily replace the lost neuro-feedback loop of patients to intervene DFU by alerting wearer once the pressure threshold is exceeded. Although a number of solutions based on analog Force Sensitive Resistor (FSR) already existed, in this paper we intended to showcase a feasible solution using digital sensors that is affordable, more versatile and adaptable to any footwear.

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Proof-of-Concept
A breadboard was used to develop an Arduino-based system as proof-of-concept that consists of 5 digital fabric sensors, Bluetooth module, Real Time Clock and MicroSD module. We chose the system to sample at 4Hz due to the following reasons: (1) the same indicative sampling rate with other similar system for easier performance comparison (2) 4Hz is deemed enough to record normal human stride.

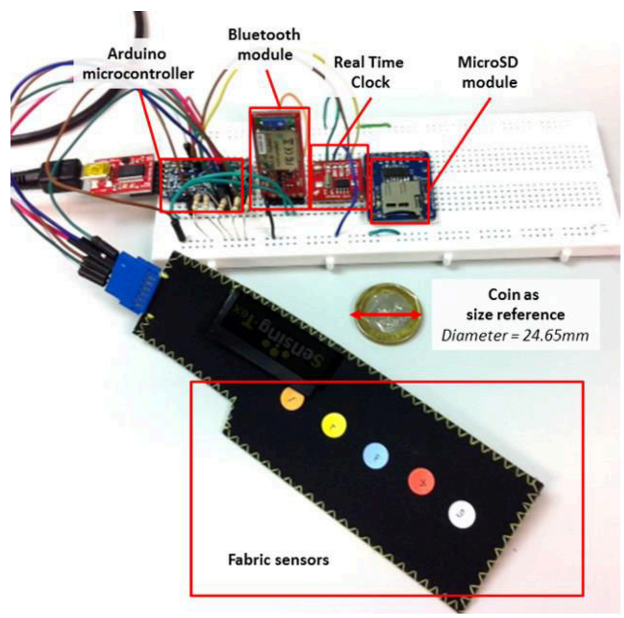

Figure 1. Proof-of-Concept using bread board.

Prototype version 1

Subsequently, the functionally complete prototype (shown in Figure 2) is designed for initial user testing. The prototype is consisted of three major components: the sensor-laden bootie, the Arduino-based platform for control and data collection, and a smart phone application for data visualization and user interaction.

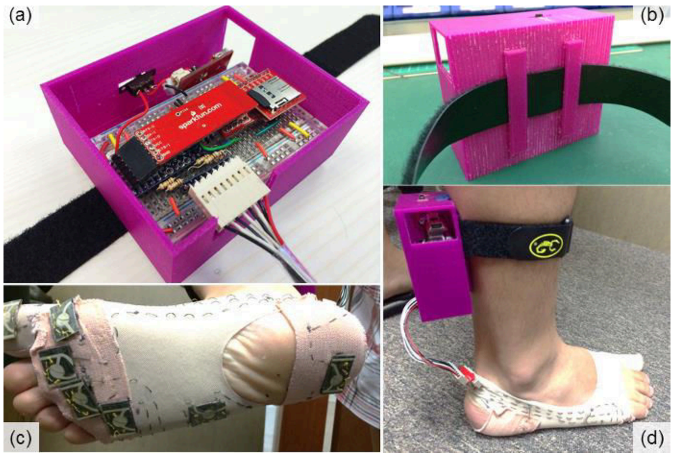

Figure 2. Prototype version 1: (a) platform front view (b) enclosure back view (c) sensor-laden bootie bottom view (d) system in use side view.

LIMITED FIELD TEST

The prototype was left with two collaborating podiatrists to collect 4-6 hours of data daily over five days. A focus group discussion was then held to document the qualitative feedback on the system.

RESULT AND DISCUSSION

Users have satisfactory feedback in terms of the battery life and the usability of the mobile app. Comfort level is acceptable for the bootie but less desirable for the enclosure case, which is expected to improve significantly with future miniaturization. Flexibility is also proven as the platform and sensors performed normally even when a user wore the prototype into sport shoes. On the other hand, the lack of analog pressure reading prevented our collaborators' hope to establish pressure-time relationship with DFU formation using this prototype. We acknowledge that is a limitation of our prototype that will be compensated in future revision.

The sub-second data set was also aggregated into per second data for easier data analysis. As each second have 3 – 4 readings (4Hz sampling rate), the aggregation is done by normalizing the number of logic '1' readings to the total number of readings per second, e.g. if 2 out of 3 readings in one particular second is logic '1', the normalized value is 0.66. In other words, we approximate the sensor was asserted for 0.66 second within that particular second. Even without the analog pressure reading, the per second data is able to show the highest frequency of pressure assertions happened at sensor S2 and S4 which is located at first and fourth metatarsal respectively. The analysis of sensor spatial data versus time also uncovers the possible cues to identify user activities as shown in Figure 3. The gait analysis algorithm can be extended using fuzzy logic [3] or combination with gyroscope data [4]. Machine learning algorithm can also be deployed in the future to customize recognition of individual gait.

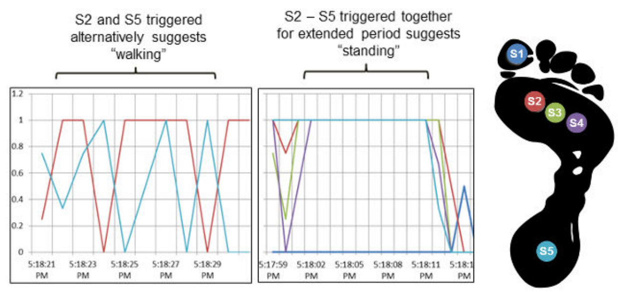

Figure 3. Activity recognition by trigger pattern and the sensor locations

CONCLUSION

We have showcased the feasibility of building an inexpensive, versatile and flexible pressure-sensing solution with digital fabric sensors. The low unit price and simplicity allows deployment of large number of sensors which in turn gives better spatial information of pressure assertion and activity tracking. However the analog pressure reading remains vital, the future work will focus in exploring to emulate analog sensors by (1) complementing digital sensors with accelerometer and (2) hybrid design with mixed number of digital and analog sensors. Once a good approximation is established, a wider Diabetic population will benefit from the DFU prevention solution.

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