Smart Insole: A Wearable System for Gait Analysis

Wenyao Xu
Electrical Engineering Department
University of California, Los Angeles
Los Angeles, CA 90095
wxu@ee.ucla.edu

Ming-Chun Huang
Computer Science Department
University of California, Los Angeles
Los Angeles, CA 90095
mingchuh@cs.ucla.edu

Navid Amini
Computer Science Department
University of California, Los Angeles
Los Angeles, CA 90095
amini@cs.ucla.edu

Jason J Liu
Computer Science Department
University of California, Los Angeles
Los Angeles, CA 90095
jasonliu@cs.ucla.edu

Lei He
Electrical Engineering Department
University of California, Los Angeles
Los Angeles, CA 90095
lhe@ee.ucla.edu

Majid Sarrafzadeh
Computer Science Department
University of California, Los Angeles
Los Angeles, CA 90095
majid@cs.ucla.edu

ABSTRACT

Gait analysis is an important medical diagnostic process and has many applications in rehabilitation, therapy and exercise training. However, standard human gait analysis has to be performed in a specific gait lab and operated by a medical professional. This traditional method increases the examination cost and decreases the accuracy of the natural gait model. In this paper, we present a novel portable system, called Smart Insole, to address the current issues. Smart Insole integrates low cost sensors and computes important gait features. In this way, patients or users can wear Smart Insole for gait analysis in daily life instead of participating in gait lab experiments for hours. With our proposed portable sensing system and effective feature extraction algorithm, the Smart Insole system enables precise gait analysis. Furthermore, taking advantage of the affordability and mobility of Smart Insole, pervasive gait analysis can be extended to many potential applications such as fall prevention, life behavior analysis and networked wireless health systems.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous

General Terms

Design

Keywords

Gait Analysis, Wireless Health, Wearable Device

1. INTRODUCTION

Gait analysis is an important human locomotion study to recognize normal or pathological patterns of walking, and its results have plenty of applications in medical programs [1], physical therapy [2], and sports training [3]. For example, with detailed gait feature analysis, therapists can quantify the rehabilitation progress of the patients after surgery, and the corresponding treatment and training can be customized according to an individual's status [4].

Normally, the quantitative gait examination is operated at a professional place, called the *Gait Lab*. A standard gait lab is roughly a 1200 square foot facility. In order to achieve comprehensive sensing and observation of gait features, traditional equipment include *eight* high-speed surrounding cameras, one big pressure sensitive carpet and a number of on-body assistive devices such as accelerometers, gyroscopes and color markers. When the patient walks in the gait lab, his motion pattern can be captured by these devices. The gait expert will analyze and recognize the walking patterns with the combined quantified data. Although gait analysis is important, it is difficult to accomplish accurately and fairly because of two reasons. First, building a gait lab is expensive. Without considering the cost and compensation of medical professionals and related expenses, it takes more than 300K dollars to setup the necessary facilities and equipment. Second, due to the burdensome equipment and precisely controlled environment, the patients always feel uncomfortable during the data collection in a gait lab. In most cases, they can not walk in their own regular style, and sensing data of gait features might always be biased, and even incorrect.

There are several prior research work on wearable devices for human gait analysis in the past. Tao Liu et al. [5] proposed a mobile gait analysis system with 3-axis accelerometer and gyroscope. Bae et al. [6] presented a Force Sensing Resistive (FSR) sensor array based system for gait analysis. Recently, Xu et al. [7] developed a Compressed Sensing based algorithm with a single acceleromater for accurate human activity recognition. All these works are helpful to understand

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the human locomotion and walking status. However, they cannot comprehensively and accurately address all gait features used in actual medical applications. There is indeed a demand of a portable system for professional level gait analysis.

In this paper, we present a wearable and affordable technology, called *Smart Insole*, which addresses the current issues in gait analysis. Different from gait lab analysis, the smart insole system integrates motion sensing components within shoe insoles. With the intelligent analysis algorithm, all important human gait features can be retrieved from the sensor data. Therefore, the Smart Insole system can monitor all types of activities in free-living without disturbing the normal life of the subject. Contrary to the cost of setting up a gait lab, the cost for the Smart Insole system can be under 200 dollars for mass production.

The remainder of the paper is structured as following. Section 2 describes the design and implementation of the Smart Insole system. In Section 3, we discuss the preliminary data from the Smart Insole System. In Section 4, we conclude and outline the future research direction and related clinical applications.

2. SYSTEM

In this section, we discuss the design concept, architecture and implementation of the Smart Insole System.

2.1 Design Requirement

Gait analysis is a complicated process, and there are hundreds of important features for identifying the normal and pathological walking patterns [8]. Some features are general and important for any kind of applications, such as cadence, stride length, stride height and speed. Some features are applicable for specific domains. For example, the pressure balance of locomotion between two feet is important for analyzing fall prevention [9], and pressure hotspot mobility is critical for diabetes foot protection and ulcer prevention [10].

According to medical literatures, there are 12 critical general gait features for miscellaneous applications. We list them and their corresponding definitions in Table 1. From an engineering point of view, it requires *precise* motion sensing and *high-resolution* under-foot pressure sensing to capture these 12 features. The detailed system architecture and hardware design will be discussed in Section 2.2.

2.2 Architecture and Hardware

The Smart Insole system architecture is shown in Fig. 1. There are three important subsystems. The first subsystem is low cost sensors for gait characterization, including 48 pressure sensors, 3-axis accelerometer, 3-axis gyroscope and 3-axis compass. The pressure sensor array is used to obtain the high-solution pressure map under foot. It is based on advanced fabric sensor technique [11] and can be efficiently integrated in the Smart Insole system. The accelerometer and gyroscope are inertial sensors, and can measure the movement information of the subject. The compass is used as the baseline when the inertial sensors (accelerometer and gyroscope) are calibrated. With 9 degrees of freedom motion sensing, the precision of motion sensing can be safely achieved.

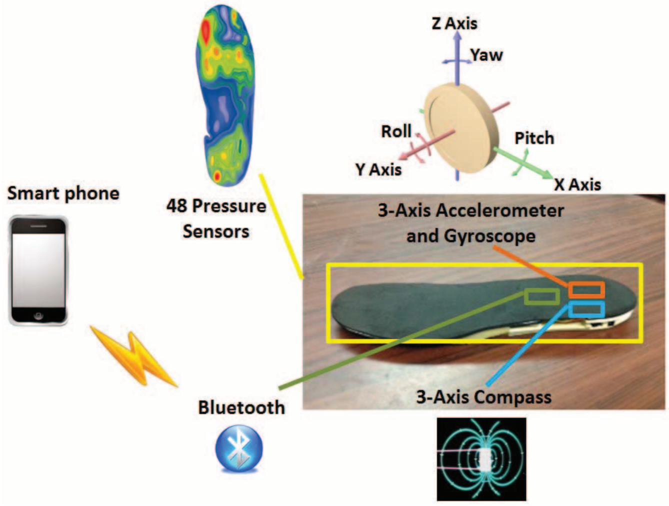

Figure 1: Sensors used in the Smart Insole system

The second subsystem is the signal acquisition and transmission module. The sensor data are quantized by 8-channel, 12-bit, 0-3.3 volt analogue-to-digital module. The sample rate can be adapted to the specific applications, up to 100 samples per second (Hz). After that, the quantified sensor data are streamed in real-time to a data aggregator. For the sake of generality and low-power issues, we use Bluetooth to transmit the data. With one 1200-mAh Li-battery, the system can continuously work for over 24 hours. Therefore, the Smart Insole system can be used daily without interruption and without charging the battery.

The third subsystem is the sensor aggregation and processing module. We developed a software on a smart phone to store and analyze the raw data it receives. For the analysis, the smart phone can calibrate the raw sensor data, fuse and remove the noise, and compute the important gait features. According to the computation load, the smart phone also could switch into router mode and upload to a data center with more powerful computing resources. The computed results can be visualized on the screen. Moreover, an effective cloud service is implemented to coordinate the remote data center. The software design will be elaborated in Section 2.3.

2.3 Software

The software system on the smart phone (see Fig. 2) consists of three stacked layers. They are the physical driver interface, data preprocessing module and data postprocessing. For the sake of real-time computing, the software is implemented with multithreading. In general, there are *six* main threads in the software program. 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 de-noising for pressure sensor data [11], calibrating inertial sensor values with filtering, and initializing the baseline with compass data. After the above steps, the data is clean, compressive and informative, and the following processing will be dispatched

Table 1: Important Features in Gait Analysis

No.	Gait Feature	Definition
1	Walking Speed	The average speed while the subject is walking
2	Stride Height	The maximum height from foot to ground during one step
3	Stride Length	The displacement of one foot from lift to landing
4	Landing Position	Position of foot when it lands, such as heel strikes first, foot lands flat, toe hits first
5	Under-foot Pressure	The fine-grained pressure distribution under foot
6	Path Distance	The total length while the subject is walking
7	Path Variation	The total length variation while the subject repeats experiments
8	Speed of Leg Movement	The speed of each leg while the subject is walking
9	Speed Difference between L&R legs	The speed variation between left leg and right leg while walking
10	Foot Orientation	The foot orientation while the subject is walking
11	Cadence	Average steps per minute while walking
12	Swing Time	The transition time of the foot from lift to landing

to the corresponding services on the next layer. As shown in Fig. 2, the remaining *four* threads receive the preprocessed data and perform two local services and two remote services, respectively.

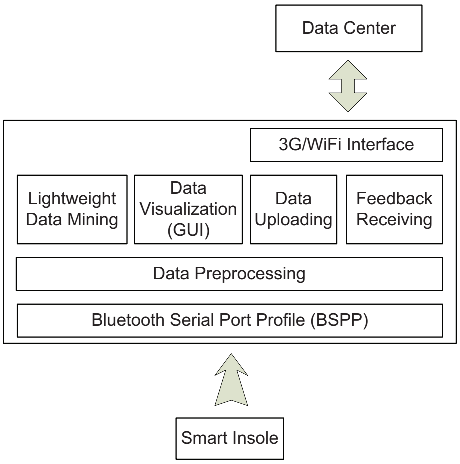

Figure 2: Stacked Software Structure

The local services includes light weight data mining and graphical user interface (GUI). Fig. 3 gives an example of local processing results. For data mining, *eight* computed results are achievable, including 1) *total pressure profile*, 2) *number of steps*, 3) *cadence*, 4) *step time*, 5) *swing time*, 6) *stance time*, 7) *stance to swing ratio* and 8) *dual limb support time*. In the GUI, pressure maps under two feet are visualized (see the up left side in Fig. 3). At the same time, the foot orientation is also displayed with the calibration motion sensor information (see the up right side in Fig. 3).

The remote services are composed of data uploading for heavy computing, and feedback receiving from data center. The remote computing and inference engine can be used to detect and classify the patient's usage context of the Smart Insole system. This accurate analytic information about the insole permits care givers to monitor the patient's walking pattern and create the feedback model to train the proper gait. The feedback also can be visualized on the screen for

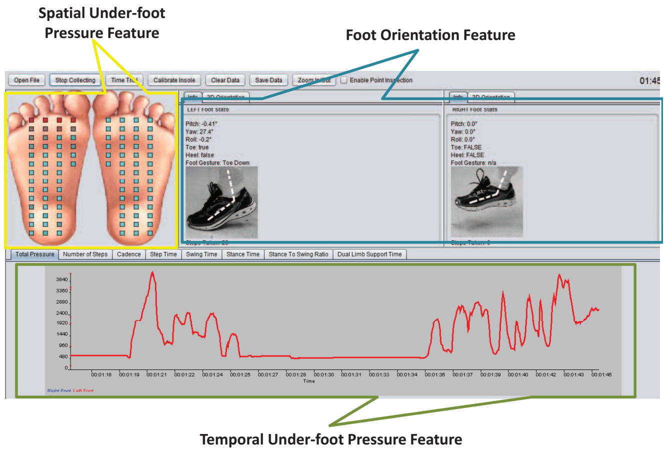

Figure 3: Software and User Interface Design

the users.

3. EVALUATION

The preliminary results from the Smart Insole system are shown in Fig. 4. The raw data streaming from the insole system was saved on the smart phone. For simplicity of the presentation, we visualize the data for 5 steps of walking from the left side insole. The computing results are based on 48 pressure sensors, 3-axis accelerometer, 3-axis gyroscope and 3-axis compass. To state the data intuitively, we selected *six* results from local data mining threads. Fig. 4(a) shows the summation profile of *five* steps. Fig. 4(b) shows the roll angular velocity. Fig. 4(c) shows the pitch angular velocity. Fig. 4(d) shows the yaw angular velocity. Fig. 4(e) shows the normalized walking speed. Fig. 4(f) shows the swing speed during walking. Based on the observation and analysis, it indicates that pressure summation profile and roll angular velocity are significantly related to step numbers. Each step is prominent in the data visualization. The general gait feature can be characterized by walking speed and swing rate. When the subject is walking constantly, the signals from these two metrics are constant as well. The individual's gait features are related to pitch angular velocity and yaw angular velocity, which should be analyzed in depth.

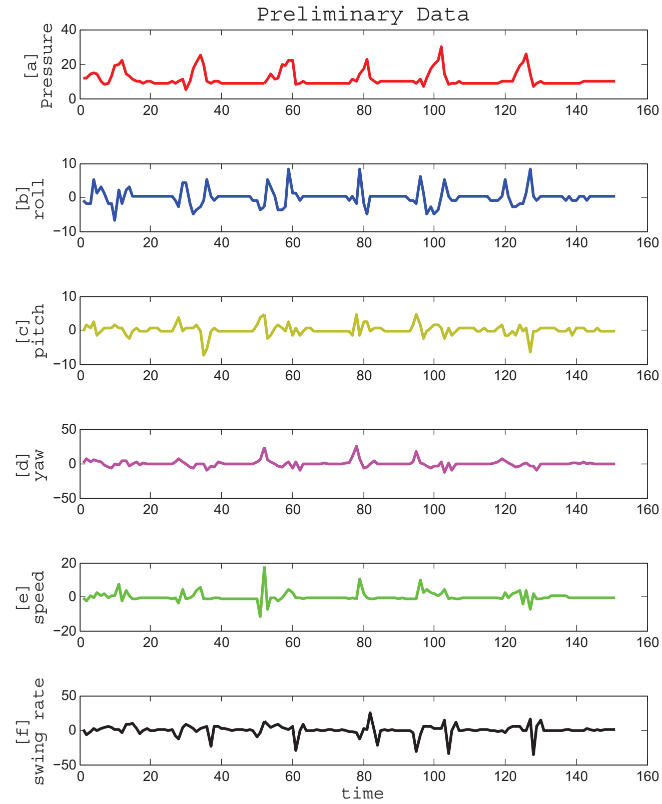

Figure 4: Data from the Smart Insole system (left foot) during subject walking activities (five steps). (a) Pressure summation of 48 sensors; (b)Roll angular velocity; (c) Pitch angular velocity; (d) Yaw angular velocity; (e) Walking speed (normalized); (f) Swing rate.

4. CONCLUSION

In this paper, we presented the design and development of the Smart Insole system that utilizes the capabilities provided by the Telehealth architecture, which may be based on commercially available microsensor, computing, and wireless technologies. We also presented preliminary data from a patient using the Smart Insole system and showed that the data can be used to analyze the patient's usage of the insole. Taking advantage of the ubiquitous internet access, the Smart Insole system can transfer the data from the patient side to the centralized servers in the medical enterprise, permitting caregivers to monitor the user gait in real-time and over long periods. Over the cloud service, the feedback could be offered by either medical professionals or statistical intelligent database. This also will enable a numerous of future applications, such as foot ulcer prevention, running pattern recognition and imbalance analysis.

Our future work to further develop and evaluate the Smart Insole system includes several objectives. First, we can offer the training to guide safe walking behavior for preventing falls or reducing the risk of falls. Second, we plan to characterize the walking patterns across a large group of patients and develop statistical models that can identify and detect the improper gait behavior leading to instability, falls and exercise, in the elderly. We plan to use these statistical models to guide and train these elderly patients to properly use a cane. Furthermore, combining Smart Insole, Smart Cane [12] and Smart Cushion [11] we developed, a complete in-home monitoring health system, including infrastructure and user end devices, could be built. Each technology is complementary to each other and jointly they supply ubiquitous sensing for complete activity monitoring.

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