

Wearable Shoe-Based Device for Rehabilitation of Stroke Patients

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Abstract—Regaining the ability to walk after a stroke is a major rehabilitation goal. Rehabilitation strategies that are task oriented and intensive can drive cortical reorganization and increase activity levels in people after a stroke. This paper describes a novel, wearable device for use with such rehabilitation strategies. The device is based on the combination of a smartphone and in-shoe sensors, and is designed to operate in free living conditions. Data collected from the device can be used for automatic recognition of postures and activities, characterization of extremity use and to provide behavioral enhancing feedback to patients recovering from a stroke. The proposed wearable platform's operation was validated in a small scale study involving three healthy individuals. The average accuracy of classification of three postures and activities was over 99%. Based on the results of validation and previously reported results on recognition of postures and activities in stroke patients, it is anticipated that recognition of postures and activities may be performed with high accuracy in free living conditions.

I. INTRODUCTION

Stroke is the leading cause of disability in older Americans [1]. Approximately 75% of individuals who have experienced a stroke have difficulty performing basic activities of daily living and over 50% have difficulty walking [2][3]. This disability leads to increased inactivity and deconditioning, which in turn can lead to further disability [4]. Increasing the amount of daily activity and walking ability are major goals for individuals who have suffered a stroke.

Current research suggests that rehabilitation strategies that are task oriented and intensive can drive cortical reorganization and increase activity levels in people with stroke [5-8]. Constraint induced movement therapy (CIMT) is one such intervention that has been shown to improve the real world use of the affected arm and hand [6]. An

important component of CIMT is behavioral enhancing strategies [9][10].

Feedback on the amount of actual activity a person performs throughout the day can be a strong behavioral motivator to increase activity levels. In neurologically intact adults, using a pedometer to provide behavioral enhancing feedback on daily walking activity is an effective method for increasing physical activity and decreasing body mass index and blood pressure [11]. Many people after a stroke cannot walk independently, in their community. A method for monitoring various types of activities other than just walking may be necessary in order to provide effective behavioral enhancing feedback on activity level. Additional feedback, such as relative use of affected extremity vs. healthy extremity, may also be useful.

This work expands upon previous research which described a novel methodology for automatic recognition of the postures and activities of patients with stroke [12][13][14]. The main focus has been converting the previously designed laboratory based system into a wearable system able to monitor a person's daily activities. The shoe based sensor will be able to monitor lower extremity activity, different postures and mobility tasks of an individual in his or her home and community. The information generated by the shoe based sensor can provide feedback to the patient and therapist on real world mobility and affected lower extremity activity. Such information can also be incorporated into the CIMT program as part of the adherence enhancing behavioral strategies.

II. SENSOR SYSTEM

A. A Wearable System

The previously designed laboratory based system consisted of a pair of wearable sensor shoes each with a pressure insole and triple axis accelerometer [12][13]. Pressure and acceleration data were sampled at 25Hz and sent over a wireless link to a base computer. This wireless link was based on Wireless Intelligent Sensor and Actuator Network (WISAN) [15] which ensured time-synchronous data collection from both shoes. A pair of shoes each equipped with sensors is used to facilitate the comparison of relative use of affected extremity vs. healthy extremity; functionality to be implemented in the future.

The goal is to replace the laboratory system with a wearable system that uses consumer friendly technology and is durable enough to be used in free living conditions. Transitioning from this laboratory based system to a wearable system presented several challenges. First, a new, portable "base station" needed to be devised which was to be

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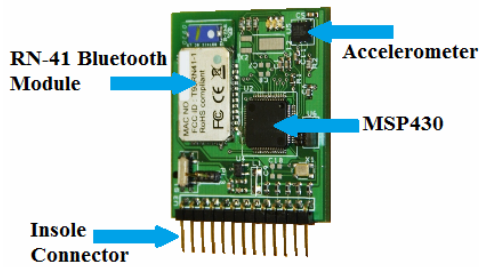


Fig. 1. The shoe sensor module.

responsible for data collection and, in the future, processing. Second, an alternative method of communication between the portable “base station,” and the wearable shoe sensors was needed.

For the “base station,” a smartphone running Microsoft Windows Mobile was selected. Since most smartphones already have Bluetooth built in, using Bluetooth, a widely proliferated technology with high consumer awareness, as the method for communication is logical. Retrofitting the previous shoe sensor with Bluetooth communications and building an application for a phone to receive this data yields a completely portable system.

The new system is composed of three major hardware components: the left shoe, the right shoe, and the smartphone. The left and right shoes are designed to use identical software and hardware due to the symmetry of their operation and interaction. The smartphone application allows for synchronized monitoring and data collection from of a pair of shoes.

B. Shoe Sensor Hardware

Two important requirements for this portable system are low power consumption and small footprint area which were the main factors in the design. The sensor module (Fig. 1) on each shoe consists of a microcontroller which is responsible for sampling of the pressure and acceleration sensors, a Bluetooth communication module and an on-board accelerometer. The shoe sensor hardware is attached to the back of the shoe and connected to the pressure sensor equipped flexible insole (Fig. 2.) which is underneath the shoe’s original insole.

The microcontroller is the TI MSP430F2417 which is an ultra-low power 16-bit RISC mixed-signal device, perfect for this portable, low power application. This microcontroller

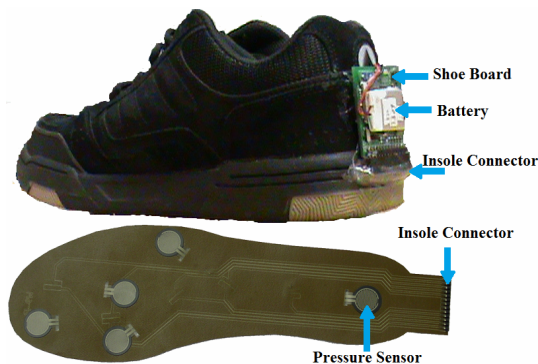


Fig. 2. The shoe with the sensor module and the insole.

comes with eight, 12-bit analog to digital converters, two universal serial interfaces, 96Kb of flash, and 8Kb of RAM.

A Roving Networks RN-41 Bluetooth module was chosen as the communication interface because of its small form factor, low power consumption (30mA in transmit/receive mode) and support of Serial Port Profile (SPP). The SPP profile allows the wearable device to appear as a virtual serial port and greatly simplifies the communication protocol.

Other selected components for the shoe include a low power, small footprint triple axis accelerometer (ADXL330) as well as power management circuitry. The resulting shoe sensor is lightweight, weighing 15grams, battery inclusive, and creates no interference with motion patterns of the wearer. The power consumption of the module in data collection mode (including all sensors) is 40mA which allows use of a 500mAh battery for continuous use during waking time (12 hours).

C. Smartphone Software

Human interaction with the system is facilitated through the smartphone software. The dual purpose smartphone software is responsible for logging the data collected from the shoes and visualizing the data. The user interface was built using Microsoft Foundation Classes, and the smartphone’s Bluetooth hardware was controlled using the WinSock library. The application is capable of performing common Bluetooth operations including: device discovery, pairing, and automatic reconnection.

For data collection purposes, the raw data is logged to comma separated value (CSV) files for later inspection on a desktop computer.

The software incorporates visual displays of the pressure sensors and accelerometers. The pressure sensor dashboard, illustrated in Fig. 3(a), indicates with color the amount of pressure applied to each sensor; red indicates more pressure, and green indicates no pressure. Accelerometer graphs pictured in Fig. 3(b) are displayed in real-time with a slightly reduced sampling rate because of the limited processing capabilities of the smartphone. These displays represent the data being logged in real-time.

D. Shoe Sensor Firmware

The shoe firmware was developed for maximum speed and minimum power usage. It was written in C using an interrupt driven architecture. For each event, such as reading the sensors or receiving data from the Bluetooth module, an

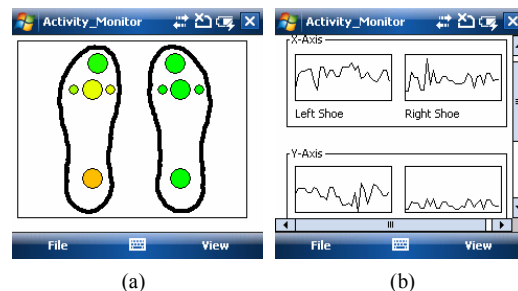


Fig. 3 Smartphone visualization of data. (a) Pressure Sensor Dashboard, (b) Accelerometer Graphs



Fig. 4. The smartphone and shoes communication routine over Bluetooth.

interrupt is generated. During an interrupt, the microcontroller is awakened from its lower power state. The appropriate flags for the interrupt are set and the microcontroller is returned to the main program loop where the necessary actions are taken and the flags are reset. The microcontroller then re-enters its low power state. To further reduce power consumption, collected data is buffered on the microcontroller and sent to the Bluetooth module in bursts. This is done to facilitate higher packet usage percentages and fewer data packets over the Bluetooth communication link between the shoe and the phone.

E. System Operation

The wearable device's main goal is objective comparison of relative use of healthy and affected lower extremities in certain activities (for example, walking). To perform such a comparison the data collected from the left and right shoe should be time-synchronous. Bluetooth time synchronization has previously been investigated by [16]. The proposed methodology utilized the host controller interface (HCI) to communicate with the Bluetooth hardware and achieve millisecond-level synchronization between wireless devices. Under Windows Mobile [17], HCI is inaccessible to standard applications including the functions to access the internal Bluetooth clock. This made the use of this scheme [16] impossible on the smartphone. Since access to the HCI layer of Bluetooth is not available, it is important to find a new method for obtaining approximately time synchronized samples.

The devised solution utilized a time-synchronization ping sent by the smartphone every second and reference timestamps derived from the internal timer on each shoe

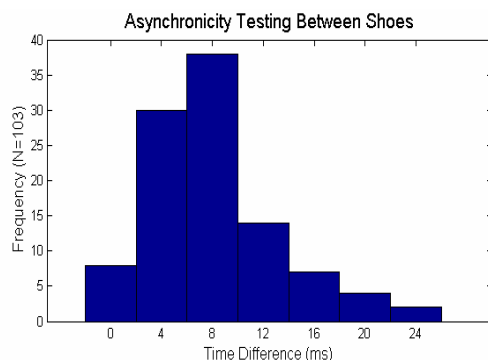


Fig. 5. Asynchronicity between the left and right shoes.

sensor. A time-synchronization ping received by the shoe from the phone provides the initial reference timestamp. Each shoe then reads the sensors every 40ms and increments the timestamp until another ping message is received. The communication routine between the smartphone and the shoes is illustrated in Fig. 4.

Upon receiving the data, the smartphone must pair the sampled data from the left shoe with the data from the right shoe. Synchronizing the samples is done by pairing the readings, one from each shoe, with identical timestamps to create a sample. Samples are then logged or displayed by the GUI as needed.

III. METHODS

System validity and operation was checked using three tests. The first two tests, performed during development, focused on the Bluetooth communication link. The third was a small study involving three participants that validated overall system operation and performance.

The first test investigated the asynchronicity of ping messages received between the shoes. During the test, the phone sent a ping message to the sensors every one second. When the sensor received the ping message, it toggled an output pin. A two channel oscilloscope was used to measure the difference between when the left and the right shoes received the ping message.

The next step was to validate that over long periods of time the samples that were paired together on the phone were actually the samples that occurred within the same sample period. A function generator was attached to the heel sensor input on both sensor boards, and was set to produce a low frequency, approximately 0.05Hz, triangle wave. This provided a perfectly synchronized input to the shoes. Given this input, the expected result should be two perfectly synchronized output wave forms; one from each shoe. Since, both sensors are receiving the same input signal it was expected that the maximum and minimum readings will line up in the data produced by the phone. The experiment was performed over a period of 5 hours.

The final test of the system verified compatibility of the proposed wearable platform with previously used laboratory system [12][13]. Specifically, compatibility with previously developed posture and activity classification model was tested in a small study with three participants. Each participant wore the device and collected one hour of data. Within that hour, participants were required to stand, walk and sit for twenty minutes each. Data collected by the phone was classified by the support vector machine trained using the original system.

IV. RESULTS

Asynchronicity testing indicated that the longest difference in arrival of ping messages is 24ms as shown in Fig. 5. Further, it is apparent that most of the time difference between sensors receiving the ping message will be minimal either 4ms or 8ms.

The waveform received by the smartphone during the long-term synchronization testing depicted a triangle wave. Visual inspection indicated that the data was continuously synchronous during the 5-hour test period because the left and right shoe waveforms were overlapping. To verify the

TABLE I. CONFUSION MATRIX

		Predicted class			Class-specific recall
		Sit	Stand	Walk	
Actual class	Sit	1928	0	0	1.000
	Stand	9	1964	10	0.990
	Walk	0	0	2028	1.000
Class-specific precision		0.995	1.000	0.995	0.9968

synchronization computationally, when each shoe recorded a maximum or minimum was compared to when the other shoe recorded a maximum or minimum. If the left and right shoe both record a maximum at the same sample number the synchronization is exact. It was determined that 62% of the time the synchronization was exact and 99% of the time the synchronization was within one sample.

Results of the small scale study indicated that recognition of postures and activities using the new system is over 99%. The confusion matrix in Table I illustrates the combined results for all three participants. The classifier used from [13] classified activities as sitting, standing, walking, ascending steps, or descending steps. For this study, walking, ascending steps, and descending steps were grouped together as walking.

V. DISCUSSION

The main goal of a wearable platform is to enable free-living studies and biofeedback to assist with stroke recovery. As such, the wearable platform should be minimally obtrusive and provide the capability for data collection and processing. The proposed device satisfies these requirements. The shoe sensors are lightweight and can be easily protected from the environment. The smartphone “base station” can be easily carried in a pocket or pouch and has the storage capacity for long-term studies. Increasingly, modern smartphones have enough processing power for on-line posture and activity recognition, which is the direction that will be taken in the future.

The testing results indicate that the wearable system performs on par with the previously used laboratory setup.

Asynchronicity testing indicated the maximum time difference between the shoes to be 24ms. This is well within the 40ms sampling period, and such the shoes should be sampling with a difference of at most one sampling period between the left and right shoes.

The second test, long-term synchronization testing proved that synchronized samples could be collected for long periods of time without degradation of the synchronization between the left and right shoes. Since 99% of the time the synchronization error was within one sample period, the system can be used to extract key gait parameters that characterize use of the healthy and affected extremities.

The final test confirmed compatibility of the sensor data between the laboratory and wearable sensor systems in recognition of postures and activities. It is important to note that the laboratory system was based on a different accelerometer model (LIS3L02AS4) and thus compatibility

testing was essential. The results indicate that data collected by the wearable system are compatible and provide highly accurate posture and activity recognition rates.

The future improvement to the system will include posture and activity recognition on the smartphone using a neural network and development of a biofeedback mechanism. Recognizing postures and activities on the smartphone will allow for a complete wearable system for use in free living conditions.

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