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Characterizing Walking Activity in People with Stroke

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Abstract— **Stroke is the leading cause of disability in the U.S. Many people with stroke have limited walking ability and are inactive. In this paper we describe a novel shoe based sensor, *SmartShoe*, and a signal processing technique to identify walking activity. The technique was validated with 6 people with walking impairment due to stroke. The results suggest that the *SmartShoe* is able to accurately identify walking activity. This device could be used to monitor walking activity as well as provide behavioral enhancing feedback to increase activity levels and walking ability in people with stroke for extended periods of time in the real world.**

I. INTRODUCTION

Stroke is the third leading cause of death and the leading cause of disability in the United States [1]. Many people who experience a stroke are disabled, require assistance for activities of daily living and mobility, and are extremely inactive. Approximately one third of people who have a stroke will be left with functional limitations as a result of their stroke. Initially after a stroke, two thirds of individuals cannot walk or require assistance to walk. After three months, one third of individuals who experience a stroke still require some form of assistance or are not able to walk [2].

Individuals post stroke who are independent walkers require less care and their level of disability is reduced as they are better able to participate in their societal roles [3]. Even individuals with relatively good recovery of walking ability are often inactive and are not able to effectively access their community [4]. As such, the recovery of walking ability and increasing activity levels is an important goal of rehabilitation [5].

Current intervention strategies to improve walking ability such as locomotor training using a treadmill and bodyweight support system and circuit training use intensive, task oriented strategies to induce neuroplastic changes in order to improve motor and functional capability in people with stroke [6-8]. However, these interventions may be missing a key ingredient, behavioral enhancing feedback, which is an important component of Constraint Induced Movement Therapy (CIMT) used in the rehabilitation of upper extremity function [9].

Behavioral enhancing strategies are used to assist the patient in taking responsibility for actively engaging in the intervention strategy and transferring gains from the clinic to increasing use of the affected limb in a real world setting. A key component of adherence enhancing behavioral strategies is the ability to monitor the use of the affected limb in the patient's home and community. This is necessary so the patient can gain an accurate view of their use of the limb and it provides important information for the rehabilitation therapist to assist with problem solving in order to overcome barriers to use.

There is a strong need for developing systems that enable the evaluation and progress of the therapy in free-living conditions, capable of accurate monitoring of walking activity. The measurement of gait activity such as steps taken and cadence provide important information on the person's walking activity. These measures can be used as a behavioral enhancing feedback to the patient[10]. Here we propose the use of a shoe-based wearable sensor system (*SmartShoe*) consisting of pressure sensors and accelerometers to accurately detect cadence and steps taken in people with stroke. This system has been successfully used for automatic monitoring of posture allocation and activities in healthy and post-stroke individuals.

II. METHODOLOGY

A. Subjects

Six individuals with chronic stroke (mean 51.67 months post stroke, 3 men and 3 women) who could ambulate without physical assistance and could provide informed consent (Mini Mental State Exam >=24) were recruited to participate in the study, table I.

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TABLE I
SUBJECT CHARACTERISTICS, MEAN (STANDARD DEVIATION)

Self Selected Gait Speed, m/s	Fast Gait Speed, m/s	Berg Balance Scale	Stroke Impact Scale 16	Lower Extremity Fugl Meyer
0.75 (0.41)	0.82 (0.41)	41.7 (13.4)	64 (11.2)	23.8 (3.8)

B. Sensor

A detailed description of the *SmartShoe* sensor system can be found in [11, 12]. Each shoe comprises five FSR sensors (Interlink, Inc.), and a 3-dimensional accelerometer based on MEMS technology. The FSR sensors were located in different foot contact points, the heel, the heads of the metatarsal bones and the great toe, soldered into a flexible Printed Circuit Board (PCB); these sensors were used to capture variations of pressure in the plantar area at all times (Figure 1). The FSR sensors respond approximately linearly to pressure exerted by the feet in different postures (standing, sitting) or activities (walking). However, the quantitative measure of the pressure is not of interest for this study, but the qualitative measure is.

The accelerometer was mounted on the heel at the back of the shoe together with the battery, power switch and the wireless board in a rigid PCB (Figure 1).

Data were sampled from these sensors at 400Hz with a 12-bit ADC converter, downsampled to 25Hz by averaging of consecutive 16 samples and sent to a smart-phone using Bluetooth and stored for later processing. The choice of sampling frequency was made as a design trade-off between battery life and physical size, both defined by power consumption during sampling and wireless transmission and time resolution of temporal gait parameters. The proposed algorithms should perform equally well for higher sampling frequencies [11]. The combination of these sensors has been successfully used to automatic recognize different postures and activities of people with stroke[13]. In this study, the variations of pressure captured by the FSR sensors were used to detect the temporal gait parameters.

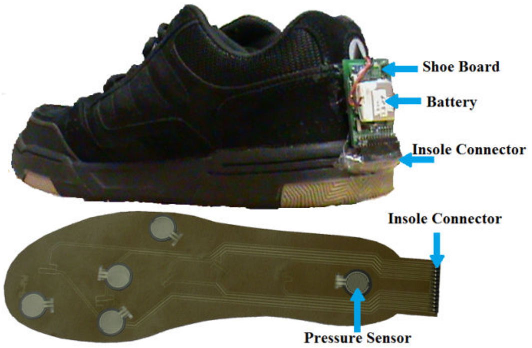

Fig. 1. FSR sensors located on a flexible PCB and wireless circuit and accelerometer located on the back of the shoe.

The integrated sensors add no significant weight to the shoe (a 5 pad sensor insole with connector weighs 17 grams) and do not cause observable interference with normal motion, posture or normal activities. Subjects who participated in the data collection expressed no discomfort or apparent change of walking behavior while wearing the shoe-sensors. The wireless sensor system is also inexpensive: the cost of parts per shoe-sensor pair is less than $100USD in single quantities and can scale down substantially in mass production.

C. Procedure

Subjects wore the *SmartShoes* while he/she completed four walking trials of a 2-minute walk at both their self-selected pace (SSP) and fastest safe pace (FSP) around a 30m oval track. Each trial was videotaped by a researcher.

D. Signal processing

For each *SmartShoes*, the pressure sensors generate the data of a qualitative signal, named *sumFSR,* which reflects the walking behavior of the subject over time, as seen in the top plot of Figure 2. The acceleration data is not used in the calculation of walking activity. These data are used to detect the Heel-strike *(H)* and Toe-off *(T)* events by defining a threshold as:

$$\tau = T_{\min} + \alpha(T_{\max} - T_{\min}) \quad (1),$$

Where T_{max} is the average level of the local maxima points, and T_{min} is the average level of the local minima points found in the *sumFSR* signal.

The parameter α is a proportional factor that adjusts the threshold as a fraction of the difference between T_{max} and T_{min}. A value of α =0.1725 was obtained experimentally to produce the lowest relative error in temporal gait analysis using a training data set[14].

The intersection points of the threshold τ with the *sumFSR* signal correspond to *H* and *T* points (Fig 3). For each foot, left *(L)* and right *(R)*, the total number of *H* and *T* are the same in order to consider the number of complete steps as a progressive count:

Left: HL_i, TL_i for $i=1,2,\dots n$ number of left steps,

Right: HR_j, TR_j for $j=1,2,\dots m$ number of right steps.

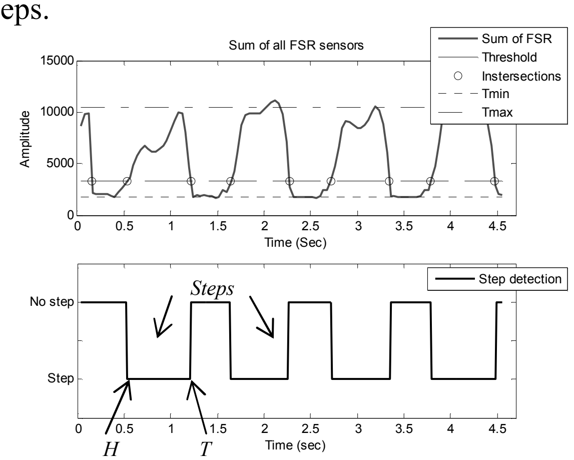

Fig 2. Signal obtained from a shoe sensor and identification of prospective *H* and *T* points using an intersection threshold τ (top), and steps detected (bottom).

After all *HL, TL, HR* and *TR* points were identified, they were used to obtain the corresponding cadence expressed in steps per minute:

$$C = (N_{\max}/t_{\max} + N_{\min}/t_{\min})/2 \quad (2),$$

where N_{max} and N_{min} are the number of maxima and minima of the *sumFSR* signal respectively; t_{max} and t_{min} are the time between the first and the last maxima and minima respectively. Cadence for each foot was calculated with equation (2) and the average between both was obtained for the final cadence computation. Detailed information on the signal processing technique is in [14].

E. Data analysis

We validated the *SmartShoes*, and accompanying signal processing techniques described above, ability to identify steps taken and cadence (steps/minute) by examining the agreement between *SmartShoe* identified steps and cadence to actual steps taken and cadence. A researcher counted the steps taken from the video data taken during each walking trial. Cadence was determined by dividing the counted steps by 2 for each 2-minute walk trial. Intraclass Correlation Coefficient ($ICC_{2,1}$) was used to examine the agreement between SmartShoe identified steps and actual steps with the affected lower extremity (ALE) and unaffected lower extremity (UALE) at SSP and FSP as well as cadence at SSP and FSP.

III. RESULTS

At SSP, participants took a mean of 83.8 (±21.5) steps with the UALE, 83.6 (±21.7) steps with the ALE at a cadence of 41.9 (±10.8) steps/minute. At SSP, the *SmartShoe* identified 83.4 (±21.4) steps with the UALE, 84.2 (±21.0) steps with the ALE at a cadence of 41.5 (±10.3) steps/minute. At FSP, participants took a mean of 90.1 (±20.4) steps with the UALE, 90.2 (±21.2) steps with the ALE at a cadence of 45.1 (±10.7) steps/minute. At FSP, the *SmartShoe* identified 89.7 (±21.2) steps with the UALE, 90.1 (±20.4) steps with the ALE at a cadence of 44.5 (±10.2) steps/minute.

The *SmartShoe* was accurate in detecting steps taken with both the UALE and ALE at SSP and FSP. The mean of the difference between the number of steps detected by the *SmartShoe* and actual steps taken over all the 2-minute walking trails at both SSP and FSP was 1.6 steps with the UALE (range 0-4) and 1.5 steps with the ALE (range 0-4). The agreement between actual steps and the *SmartShoe* detected step counts and cadence was high, $ICC_{2,1}$ >0.99 (p<0.000) for steps taken with the UALE and ALE and cadence at both SSP and FSP, Table II.

TABLE II
Agreement Between SmartShoe and Actual Steps, $ICC_{2,1}$ (95% CI)

	$ICC_{2,1}$	$ICC_{2,1}$ 95% CI
ALE Steps @ SSP	0.996	0.991-0.999
ULE Steps @ SSP	0.996	0.990-0.998
Cadence @ SSP	0.994	0.986-0.998
ALE Steps @ FSP	0.996	0.991-0.999
ULE Steps @ FSP	0.996	0.991-0.998
Cadence @ FSP	0.993	0.977-0.997

IV. DISCUSSION

The *SmartShoe* and accompanying signal processing techniques was able to accurately characterize walking activity in people with stroke. The *SmartShoe* demonstrated as good or better accuracy in detecting the number of steps in people with stroke than other activity monitors that are currently on the market [15-17].

Compared to other systems reported in literature, the *Smartshoe* resulted in a very high ICC agreement. The study reported in [18] shows reliable results using the GAITRite system as a method for estimating temporal and spatial parameters of gait, resulting in ICCs of 0.83 and 0.82 in cadence estimation for young and older people respectively. In [19], the implementation of two systems was evaluated for acquisition of spatiotemporal gait parameters. The first was based on an array of 5 accelerometers, and the second consists on footswitches located at the heel of foot. Results showed a strong agreement between the two methods, with ICC >0.85 for each temporal measure.

Additionally, the *SmartShoe* requires only that the user put on their shoes as the sensors are embedded on the shoe. Other systems require the user to place multiple sensors on different locations on their body. This may not be practical for everyday use outside a research environment.

We envision the *SmartShoe* system as not only a means of monitoring and measuring walking activity and overall activity levels in people with stroke but as part of a comprehensive rehabilitation intervention to promote increased activity levels and walking ability in people with stroke. The ability to accurately monitor use of the affected extremity, walking activity and overall activity level are key to developing effective behavioral enhancing strategies. Without this information the patient cannot get an accurate picture of the use of their affected extremity nor can the physical therapist assist the patient in developing strategies to increase activity in the home and community environments.

V. CONCLUSION

Our results indicate that the *SmartShoe* and our detection algorithm is a valid method of detecting steps taken and intensity of walking activity in people with stroke. The *SmartShoe* system could be used to measure the amount and intensity of walking activity in the real world, as well as to provide behavioral enhancing feedback as part of a comprehensive rehabilitation intervention to improve walking ability in people with stroke.

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