Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Development of a Quantitative In-Shoe Measurement System for Assessing Balance: Sixteen-Sensor Insoles

Stacy J. Morris Bamberg, *Member, IEEE,* Paul LaStayo, Lee Dibble,
Josh Musselman, Swarna Kiran Dasa Raghavendra

Abstract—**This work presents the first phase in the development of an in-shoe sensor system designed to evaluate balance. Sixteen force-sensitive resistors were strategically mounted to a removable insole, and the bilateral outputs were recorded. The initial results indicate that these sensors are capable of detecting subtle changes in weight distribution, corresponding to the subject's ability to balance. Preliminary analysis of this data found a clear correlation between the ability to balance and the state of health of the subject.**

I. Introduction

PREVENTING falls in elders is likely to become increasingly important with the expected change in demographics over the next several decades and the associated increase in life expectancy. Falls are a large source of morbidity and mortality in the elderly population in general [1-3], and in the Parkinsonian population specifically [4]. Falls in these populations can result in serious injuries, hospital stays, increased healthcare costs. In addition, following even a single fall, fear of falling again increases [5]. If self-confidence and mobility are not restored, these factors can lead to a downward spiral of decreased quality of life and muscle atrophy.

Falls can result from many factors, including decreased vision, prescription medications, environmental hazards, as well as impaired balance, changes in posture and gait changes [6]. To date, investigation of changes in gait due to impaired balance have focused on a few select parameters, such as gait speed and variability in stride timing [7-8]. In both the elderly and Parkinsonian populations, variation in stride-timing has been shown to correlate with the risk of falling [3, 8].

Manuscript received April 24, 2006. This work was supported by a research grant from the American Parkinson Disease Association.

S.J.M. Bamberg. is an assistant professor with the Department of Mechanical Engineering, University of Utah, Salt Lake City, UT 84112 USA (phone: 801-585-9081; fax: 303-555-5555; e-mail: sbamberg@eng.utah.edu).

Paul LaStayo is with the University of Utah Division of Physical Therapy, Salt Lake City, UT 84112 USA (email: Paul.Lastayo@health.utah.edu)

Lee Dibble is with the University of Utah Division of Physical Therapy, Salt Lake City, UT 84112 USA (email: Lee.Dibble@hsc.utah.edu)

Josh Musselman is with the Department of Mechanical Engineering, University of Utah, Salt Lake City, UT 84112 USA (e-mail: joshemusselman@hotmail.com).

Swarna Kiran Dasa Raghavendra is with the Department of Mechanical Engineering, University of Utah, Salt Lake City, UT 84112 USA (e-mail: drswarnakiran@yahoo.co.in).

Currently, balance is typically assessed by the following tests: the Activities-specific Balance Confidence Scale, a 16-item questionnaire; the Berg Balance Scale, a 14-item function test scored from 0-4 according to task completion; and, the One Leg Standing Test, scored based on the number of seconds the subject can stand on one leg [9].

Previous work [10-11] resulted in a wireless, wearable system developed to measure several relevant gait analysis parameters outside the confines of a traditional motion laboratory. The results demonstrated that this type of wearable system can be highly capable of detecting heel-strike and toe-off, as well as estimating foot orientation and position. This system was evaluated on persons with normal gait and persons with Parkinson’s disease, and was also able to detect a difference in stride time variability. The standard deviation of stride time in 26 samples of Parkinsonian gait was .21 s (17.2%), more than double the 0.09 s (8.4%) in 48 samples of healthy gait [11]. This system included four force-sensitive resistors (FSRs).

Our goal is to develop an in-shoe measurement system capable of quantitatively assessing balance in a manner similar to the existing methods described above, as well as measuring parameters likely to correlate with balance that are not easily measured in the clinic at this time. Thus, in addition to determining stride time variability, such a device should be able to evaluate foot pressure distribution, foot accelerations and velocities, and real time foot range of motion. This device also needs to be able to accurately measure and collect gait data independently of the traditional laboratory setting, both to be readily implemented in a clinical setting, as well as to provide a more real-life measurement of gait instability and variability. The ability to provide mobile comprehensive gait monitoring over extended periods of time outside the lab will facilitate characterization and measurement of balance and falls, and could ultimately lead to real-time intervention to prevent falls.

This paper presents the initial results from the development of sixteen-sensor insoles; work is ongoing to further develop motion analysis using accelerometers and gyroscopes [12]. After the final system has been developed, it will be used to assess balance in a number of ways. Following the Berg Balance Scale, the subject will be asked to stand for two minutes, and to rise from the seated position without using support. In addition, the One-Leg Standing Test on the subject’s preferred leg, for up to 30 s, without support. The subject will be asked to walk continuously for five minutes; this data will be used to evaluate stride time variability, as well as force distribution, foot accelerations and velocities, and respective variabilities. These tests will be carried out on a group of subjects both before and after a 12 week high intensity strength training program that has previously shown positive results for a Parkinson's population [13].

II. Materials and Methods

A. Hardware

The sixteen-sensor insoles (SSI) consist of sixteen force-sensitive resistors (FSRs) strategically affixed to the bottom of removable insoles. The FSRs are commercially available from Interlink Electronics [14], and the removable insoles were made by Dr. Scholl's [15]. Two sets were made, one men's size 10, and one women's size 6; a photograph of the men's insole is shown in Fig. 1. The bulk of the sensors were placed in the metatarsal region of the insole. When fitting subjects with feet larger or smaller than these insoles, the insole position was adjusted in the shoe such that the metatarsal sensors aligned with the metatarsal location in the shoe, and the large sensor in the heel region was adjusted to be directly beneath the heel pad. All of the sensors, except the large sensor in the heel region, were enclosed in shrink-wrap for protection.

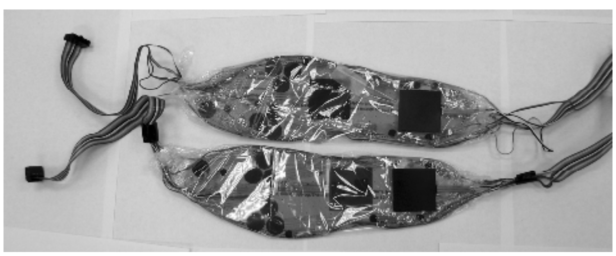

Fig. 1. The underside of the Sixteen Sensor Insole, showing the sizes and locations of the force sensitive resistors. The side showing was placed down next to the insole of the shoe, and the subject's foot made contact with the opposite side of the insole.

The circuitry for the sensors is currently located on the outside of the shoe on two printed circuit boards containing conditioning electronics for the FSRs (a current-to-voltage converter), two 8x multiplexers, two 2/3A lithium batteries, voltage regulators to provide ±5V, and a fuse to shut off power in the unlikely event that more than 300 mA was drawn from the batteries. The FSRs were connected via two ribbon cable headers; one exited the shoe behind the heel, and the other exited at the toe-end of the tongue of the shoe, as shown in Fig. 2. A 3 m tether connected to the system to a National Instruments USB-6009 data acquisition device and a small external circuit used to set the multiplexer outputs, such that each sensor was read at 250 Hz. Data were collected using a LabView program, and exported for analysis in MATLAB.

It is worth noting that the conditioning electronics were selected for providing a nearly linear response from the

Fig. 2. The circuitry for the Sixteen Sensor Insole, mounted on a sample pair of shoes. The 3 m tether is connected to a DAQ board and a computer for control of the multiplexers and data acquisition.

force sensitive resistors. These can be calibrated, but have large manufacturing variations between sensors, and in addition are affected by temperature and humidity, as well as the type of loading. Both temperature and humidity are hard to control for in a shoe. The loading of the sensors is non-ideal, in that comfortable shoes have some flexibility in the insole, while the sensors have more reliable results when pressed against a smooth flat surface. Though these seem to indicate that these sensors are a poor choice, in reality, on an individual level, they work well on an absolute scale. That is, for a given sensor, loaded vs. unloaded is readily apparent, and with appropriate conditioning electronics, such as the current to voltage divider circuit, a linear output can be obtained. If desired, each could be calibrated individually, but since we are not interested in total force, but rather variation in force, the raw data (in V) is evaluated.

B. Testing Protocol

Subjects were recruited from participants at the University Rehabilitation and Wellness Clinic at the University of Utah. This population includes persons with Parkinson's disease, persons with general balance instability. Spouses and friends who were accompanying participants, and who had no known gait abnormalities were used as aged-matched persons with healthy gait.

For this analysis of the SSI, subjects were fitted with shoes, and asked to complete the following tasks: two-legged standing with feet at shoulder width apart for one minute, one-legged standing on each foot for ten seconds (support allowed), and rising from a chair to a standing position (using support was allowed). These tests were modified from those described in the introduction, to allow maximum comfort to the subject, given that the shoes were on a short (3 m) tether to the computer.

III. Results

Seven subjects were evaluated; the characteristics of these subjects are detailed in Table I. These subjects were recruited as described above, and were all fitted with the large set of insoles, shown in Fig. 1. Two samples of standing data were used for each subject.

TABLE I
SUBJECT CHARACTERISTICS

Group	Males	Females	Average Age [Years]
Healthy Gait	1	1	67.5
Parkinsonian Gait	3	1	80.3
Non-Parkinsonian Balance Problems	1	0	84

Three types of data were collected from each of the subjects: standing with both feet on the ground, standing on one leg (with support), and a seated chair rise (with support). The standing data turned out to be the most useful, because the amount of support required by the Parkinsonian group and the person with balance problems was significantly more than in the control group with healthy gait. (As mentioned above, in future tests, support will not be allowed, but because of the nature of the tethered shoes with the large batteries, the comfort of the volunteer subjects was a priority.) The results from the standing trials are shown in Table II; results reported are the mean value of the standard deviations calculated for each of the 32 sensors (in two insoles, left and right) for two trials per subject, as well as the standard deviation of these results.

TABLE II
STANDARD DEVIATIONS OF FORCES DURING STANDING

Group	Mean of the Standard Deviations [V]	Standard Deviation of the Std. Dev. [V]
Healthy Gait	0.029	0.016
Parkinsonian Gait	0.065	0.019
Non-Parkinsonian Balance Problems	0.102	0.013

Fig 3 shows three samples of sensor outputs, one from each group (the older subject in the healthy gait group is shown below). For clarity, only the eight sensors in the metatarsal region of the right foot are plotted (the other eight sensors are spread between the toe, midsole, and heel, as shown in Fig. 1). Five representative seconds of each sample were selected.

IV. DISCUSSION

This initial study of the sixteen-sensor insole investigated standard deviations of the force sensitive resistors outputs during one minute (or longer) of two-legged standing. In all cases, gross motion of the patients' feet was unobservable: the outside of the shoes did not move. However, as the data clearly shows, small fluctuations in the weight distribution can be readily measured, as corresponding to changes in the output of the force sensitive resistors.

In Fig. 3, the graph of sensor outputs for the subject with healthy gait demonstrates that small changes in the weight distribution over time are to be expected. In this plot, changes happen with the frequency of about 1Hz. For the two subjects with healthy gait, the mean standard deviation was 0.029V, as shown in Table II.

Parkinson's disease results in small tremors. Though not visible from watching the shoes of a person with Parkinsonian gait while standing, Fig. 3 shows that these small tremors can be readily detected, and occur at a higher frequency (multiple changes per second). Correspondingly, the mean standard deviation across all sensors was 0.065V, more than double that seen in the subjects with healthy gait.

During testing, we were fortunate to be able to evaluate one person who has balance problems, but does not have Parkinsonian gait. As shown in Fig. 3, for this subject, the change in force distribution occurred over much longer time scales than in the subjects with health gait. In addition, the magnitude of the change was much larger than the changes seen in either of the other groups. This large magnitude change resulted in a mean standard deviation across all sensors of 0.102 V, more than triple that see nin the subjects with healthy gait.

Though these results must be considered as preliminary, since only a small number of subjects have been observed to

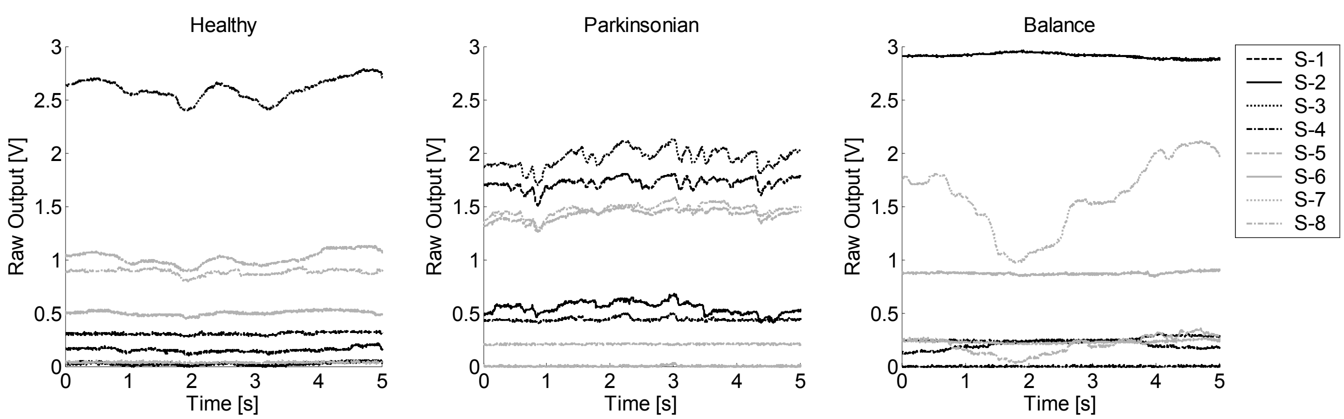

Fig. 3. Samples of sensor outputs for the eight force sensitive resistors located underneath the metatarsals of the right foot; samples are shown for each of the three subject groups for five seconds of standing.

date, the results do indicate that the sixteen-sensor insole may be quite useful as a tool for evaluating balance. In particular, the large difference between the person with balance problems and the healthy group indicates that there is indeed a measurable change in standard deviation of the force sensitive resistor outputs. Though the absolute changes detected are small relative to the 3V output range of the sensors, individual sensors have larger changes, as evidenced by the graphs in Fig. 3. However, it is worth noting that the standard deviation across the standard deviations of individual sensors is approximately the same for each of the three groups. Finally, in each of the graphs in Fig. 3, there are multiple sensors with very low readings, indicating that those sensors were located in an area of low pressure underneath the subject's foot. Thus, a more sophisticated method of evaluating the sensor outputs, considering only those sensors loaded to a prescribed level may result in a better discrimination between these groups.

V. Conclusion and Future Work

These initial tests indicate that an in-shoe pressure sensing system can provide an indication of balance by simply evaluating the standard deviation of each of the force sensors in the sixteen-sensor insole.

Our immediate future work will focus on turning this insole into a true in-shoe system, by replacing the external data collection with an on-board microcontroller and data storage (and using smaller batteries); we plan to imbed the circuitry within the heel of the shoe. This will allow us to continue to evaluate the balance while standing two feet, while also expanding to evaluating walking (for instance, to measure the variation in stride timing), and in more dynamic tests such as one-leg standing that require a non-tethered system. In addition, we are simultaneously working on an inertial measurement system for evaluating motion over small time-scales (such as a single step), and plan to integrate this with our sixteen-sensor insole in the near future to allow us to evaluate motion of the foot.

The first major application for our system will be to use it to evaluate subjects before and after (and likely during) a 12 week high intensity strength training program, in order to investigate the effects of the training program on balance.

Acknowledgment

We thank Heather Hayes, PT, DPT, and D. James Ballard, PT of the University Rehabilitation and Wellness Clinic for their assistance in recruiting volunteers. We are grateful to the volunteer subjects, and thank them for donating their time.

References

[1] Hill, K., et al., "Falls among healthy, community-dwelling, older women: a prospective study of frequency, circumstances, consequences and prediction accuracy." Aust N Z J Public Health, 1999. 23(1): p. 41-8.

[2] Kannus, P., et al., "Fall-induced injuries and deaths among older adults." Jama, 1999. 281(20): p. 1895-9.

[3] Grimbergen, Y.A., M. Munneke, and B.R. Bloem, "Falls in Parkinson's disease." Curr Opin Neurol, 2004. 17(4): p. 405-15.

[4] Rizzo, J.A., et al., "Health care utilization and costs in a Medicare population by fall status." Med Care, 1998. 36(8): p. 1174-88.

[5] Beliz Belgen, Marianne Beninato, Patricia E. Sullivan and Khushnum Narielwalla, "The Association of Balance Capacity and Falls Self-Efficacy With History of Falling in Community-Dwelling People With Chronic Stroke," Archives of Physical Medicine and Rehabilitation, Volume 87, Issue 4, April 2006, Pages 554-561.

[6] K Delbaere, N Van den Noortgate, J Bourgois, G Vanderstraeten, W Tine, D Cambier. "The Physical Performance Test as a predictor of frequent fallers: a prospective community-based cohort study." Clinical Rehabilitation 2006; 20: 83-90

[7] Sheridan, P.L., et al., "Influence of executive function on locomotor function: divided attention increases gait variability in Alzheimer's disease." J Am Geriatr Soc, 2003. 51(11): p. 1633-7.

[8] Hausdorff, J.M., D.A. Rios, and H.K. Edelberg, "Gait variability and fall risk in community-living older adults: a 1-year prospective study." Arch Phys Med Rehabil, 2001. 82(8): p. 1050-6.

[9] Hawk C, Hyland JK, Rupert R, Colonvega M, Hall S. "Assessment of balance and risk for falls in a sample of community-dwelling adults aged 65 and older." Chiropr Osteopat. 2006 Jan 27;14:3.

[10] Morris SJ, "A shoe-integrated sensor system for wireless gait analysis and Real-Time Therapeutic Feedback," Sc.D. dissertation, Harvard/MIT Division of Health Sciences and Technology, Cambridge, MA, June 2004.

[11] S.J.M. Bamberg, A.Y. Benbesat, D.M. Scarborough, D.E. Krebs, J.A. Paradiso, "Gait Analysis Using a Shoe-Integrated Wireless Sensor System." IEEE Transations on Information Technology in Bioengineering, In Submission.

[12] Johnson EA, Minor MA, Bamberg SJM, "A State Estimator for Rejecting Noise and Tracking Bias in Inertial Sensors," unpublished.

[13] LaStayo PC, Ewy GA, Pierotti DD, Johns RK, Lindstedt S, "The positive effects of negative work: increased muscle strength and decreased fall risk in a frail elderly population." J Gerontol A Biol Sci Med Sci. 2003 May;58(5):M419-24

[14] Interlink Electronics, available: http://www.micronavlink.com/technology.html

[15] Dr. Scholl's Air-Pillo Cushioning Comfort, available: http://www.drscholls.com/product.aspx?prodid=64