Gait Analysis Using a Wireless Shoe-Integrated Sensor System

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***Abstract*—This paper describes a wireless wearable system capable of measuring many parameters relevant to gait analysis, and developed to provide quantitative analysis of gait outside of the confines of the traditional motion laboratory. The extensive sensor suite includes three orthogonal accelerometers, and three orthogonal gyroscopes, four force sensors, two bi-directional bend sensors, two dynamic pressure sensors, as well as electric field height sensors. The "GaitShoe" was built to be worn on any athletic shoe, without interfering with gait, and was designed to collect data unobtrusively, in any environment, and over long periods of time. The calibrated sensor outputs were analyzed and validated with results obtained simultaneously from The Massachusetts General Hospital Biomotion Lab during subject testing. The GaitShoe proved highly capable of detecting heel strike and toe off, as well as estimating orientation and position of the subject.**

***Index Terms*—Biomedical measurements, legged locomotion, multisensor systems, telemetry.**

I. Introduction

CLINICAL gait analysis is the investigation of the pattern of walking. At present, gait analysis is primarily carried out in one of two ways: in a motion laboratory, with full analysis of the motion of all body segments using highly accurate computer-based force sensors and optical tracking systems, or in an office with the clinician making visual observations. The first method is expensive, requires the maintenance of a dedicated motion lab, and uses cumbersome equipment attached to the patient, but produces well-quantified and accurate results for short distances. The second method is inexpensive and does not require any equipment, but the results are qualitative, unreliable, and difficult to compare across multiple visits.

There is a need for a low cost device that falls in between these two methods, and is capable of providing quantitative and repeatable results. In addition, there is a need for long term monitoring of gait, as well as quick diagnosis of chronic walking problems. Also, there is a need to be able to quantitatively analyze gait for patients who do not have access to motion analysis labs, such as is the case in economically disadvantaged locations.

As such, there has been considerable previous work in both research and commercial fields focused on the development of more mobile methods of analyzing gait. The obvious advantage of directly measuring the pressure distribution beneath the foot has driven many of the early shoe-based systems. The shrinking size of data storage has further encouraged the development of non-tethered systems.

In 1990, Wertsch *et al* [1] developed a system for measuring the pressure distribution beneath the foot, using seven force sensitive resistors (FSRs), located under seven high pressure points corresponding to the five metatarsal heads, the big toe, and the heel center. This tethered system gave detailed information about the pressure distribution beneath the foot, and provided those results in real-time. Data collected with their device were used to quantify the differences between shuffling and walking [2], and between sensate and insensate (no or little sensation in the foot) subjects [3]. In the latter study, the results led to a caution against drawing conclusions from a short segment of gait analysis in patients with sensory impairment, as a large step-to-step variation was found in these patients, emphasizing the need for a device capable of collecting data over a long time period.

In 1994, Hausdorff *et al* [4] developed a system capable of detecting several of the temporal gait parameters. Their system consisted of an insole with two FSRs positioned under the heel and in the general area under the toes and metatarsals, ultimately connected to a circuit board and battery pack worn on the ankle [5], [6]. Validation of the data by comparison to data collected simultaneously from commercial force plates

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indicated their device found stance duration to be within 3% and swing and stride duration within 5% as compared to the results from the force plate. Their insole has been used to find patterns in gait [7], which they have been able to use to predict the maturation of gait in children [5], and the likelihood of falling in the elderly [6], demonstrating that only two FSRs are necessary to distinguish some types of abnormalities in gait from healthy gait.

More recent work resulting in shoe-based sensor systems with increasingly sophisticated measurement capabilities have been driven by subspecialty interests in gait analysis. For diabetics, Morley *et al* [8] have developed an insole-based system to quantify the conditions inside the shoe, with the goal of being able to predict progression of skin breakdown and ulceration in diabetic patients with peripheral neuropathy. Their laminated insole had pressure, temperature and humidity sensors designed to investigate the conditions at the foot interface, and was connected to an electronics module and batteries located in a plastic enclosure strapped to the calf of the subject. In initial work with their device, they were able to detect quantitatively distinct variations in pressure patterns that corresponded to different activities, and were able to correlate their results with previous studies [9].

Another area of research driving the development of devices capable of capturing information about gait is the use of neuroprosthetics for walking assistance. Neuroprosthetics require inputs to trigger the functional electrical stimulation (FES) used to assist the patient in making the walking motions. Pappas *et al* first developed a device consisting of three FSRs are located on an insole (one under the heel, and two at the first and fourth metatarsal heads), and a gyroscope attached to the back of the shoe, placed such that the sensing axis was perpendicular to the sagittal plane [10]. With this system, they implemented a pattern recognition algorithm that used data from the FSRs and the gyroscope to define the transitions between two distinct phases (stance, swing) and two distinct events (heel-off, heel-strike). Their algorithm was validated by comparison to results from a commercial motion analysis system using optical motion analysis (a Vicon 370 from Oxford Metrics Ltd.). As compared with the commercial system, their algorithm achieved a 99% detection rate for normal subjects and a 96% detection rate for subjects with impaired gait, with a detection delay under 90 ms; these results demonstrated that on-shoe systems with gyroscopes and FSRs are able to achieve comparable results to commercial optical systems. More recent work by Pappas *et al* has resulted in an insole-only system where the gyroscope and a microcontroller have been embedded in the insole [11]. Using the results from their previous work, the system was tested on two subjects with incomplete spinal injury resulting in drop-foot. The system was used to trigger functional electrical stimulation (FES), and demonstrated a functional benefit of using it for both subjects, while walking horizontally, uphill, downhill, and while sitting and standing.

Other research platforms include instrumented walkways [12], "piezo-dyanomometric" platforms [13], or instrumented floors [14], [15]. Such systems can determine parameters relating to the pressure distribution, as well as about stance and swing duration, but cannot provide information about the motion of the foot above the platform. In addition, research platforms have been developed to recognize gait without instrumenting the subject (generally motivated for use as a biometric identifier), primarily by videotape analysis [16], [17], [18], [19], and also through the use of radar [20].

Commercial systems are numerous, and cover a wide range of applications, including tap-dance [21] to golf-swing analysis [22]. A very popular application is the use of inertial sensors to provide athletes with information, particularly for runners, such as the products available from Acceleron [23], Reebok (the Traxtar) [24], FitSense [25], Vectrasense [26], and Adidas [27], [28]. NCSA's Cyberboots use a pressure sensor array in an overshoe to provide walking interaction in a virtual reality environment [29]. For medical applications, Tekscan and Clevemed, among others, have developed insoles which measure pressure distribution [30], [31]. In addition, MiniSun markets "The IDEEA LifeGait System", which uses the outputs of accelerometers placed on various parts of the body with "artificial intelligence" algorithms to determine a number of parameters relating to gait and motion [32].

Finally, the research presented in this paper grew out the Expressive Footware project developed by Dr. Paradiso and students in the Responsive Environments Group at the MIT Media Lab [33]. The Expressive Footware project resulted in a pair of running shoes that were each equipped with a wireless sensor board and an instrumented insole. Each insole measured dynamic pressure at the heel, bidirectional bend of the insole, the height of each foot above a conducting mat on the floor, and had three FSRs (two placed roughly at the medial and lateral metatarsal heads, and one outside the shoe, mounted at the toe). Each sensor board was permanently attached to the lateral side of the shoe, and contained a gyroscope for the angular rate of the foot about the vertical axis, a three-axis compass to determine the orientation of the foot relative to the Earth's local magnetic field, two axes of acceleration (the two axes in the plane of the sensor card), and three axes of shock acceleration. An integrated sonar receiver on each sensor board, in conjunction with four sonar transmitters on the floor, provided the position of each foot in the plane of the floor. This system was built for control, not for measurement; the sensor outputs were used to directly control real-time musical outputs, generated by a computer that interpreted the base-station data stream with an elaborate rule base. This highly instrumented shoe was worn by dancers and the outputs of the sensors were used to interactively control music. It reached high acclaim in the dance community, and was recognized with the Discover Award for Technical Innovation in 2000 [34].

The research described in this paper sought to create a system to provide instrumented gait analysis outside of traditional, expensive motion labs. Such a system has the potential to be highly informative by allowing data collection throughout the day in a variety of environments, thus providing a vast quantity of long-term data not obtainable with current gait analysis systems. The "GaitShoe" system has been designed with components configured to minimally affect gait, and is readily fixed on typical athletic shoes. The GaitShoe was replete with sensors, with the goal of measuring more parameters than would otherwise be necessary for any one application, essentially providing a wearable podiatric laboratory. The power source was contained on-shoe, and wireless protocols were used to communicate between shoes and to transmit the data to a base-station; no cables of any sort were attached to either shoe.

This research evaluated the system both in persons with normal gait, and in elders with Parkinson's disease (PD). The results were validated by comparison with data collected simultaneously by the system in use at the Massachusetts General Hospital Biomotion Laboratory.

VI. Discussion

The development of the GaitShoe has resulted in a wireless wearable system with an unprecedented number of sensors designed to capture information that can characterize gait of both feet. The system costs under $500 per foot in prototype quantities and the hardware for a single shoe weighs under 300 g. The hardware is readily fixed to a variety of typical walking shoes, and data can be continuously collected over a few hours.

The validation results indicate that the GaitShoe can be further developed into a true wearable podiatric laboratory, which could be of great use in evaluating gait over longer periods of time than are available in motion laboratories, as well as allowing the evaluation to be carried out in a neutral environment, such as the subject's home. It would also allow the evaluation of subjects who are without access to a motion laboratory.

The simplified analysis of the motion of the foot, using only the x- and y- accelerometers and the z- gyroscope, resulted in reasonable estimations of the pitch and stride length. The GaitShoe pitch had an RMS error of 5.2º, and the GaitShoe pitch extrema had a standard deviation from the BML of 6.6º, and was well-correlated, with a Pearson's correlation of 0. 992. The GaitShoe stride length had a standard deviation from the BML of 13.6 cm, and a Pearson's correlation of 0.841, with an RMS error of 8.5 cm. Errors in the pitch affect the calculations of stride length, since the pitch is used to both subtract the gravitational component of the acceleration, as well as to determine the dynamic component of the acceleration along the XROOM coordinate from the x- and y- accelerometers. Thus, improving the GaitShoe pitch, by decreasing the standard deviation while maintaining the high correlation to the BML, will likely result in improved GaitShoe stride length calculations. In addition, the standard deviation between the time points of the GaitShoe extrema and the BML extrema was 24.2 ms, with a Pearson's correlation of 1.000: decreasing the time deviation in the pitch will likely also improve the stride length results. Future work to improve the GaitShoe pitch and stride length calculations will incorporate all six IMU measurements, covering three perpendicular axes of angular velocity and acceleration.

The multi-sensor GaitShoe determination of heel strike and toe off was highly successful, as compared to the BML heel strike and toe off time. Though the standard deviation of the heel strike time was 22.9 ms, the Pearson's correlation was 0.999, and, similarly, though the standard deviation of the toe off time was 16.9 ms, the Peasrson's correlation was 1.000. The determination of the GaitShoe toe off time used the calculated pitch, so, again, improvement of the pitch will likely propagate through to improve the standard deviation of the toe off time. The heel strike time used either the presence of a spike in the x-accelerometer, or, if no spike was present, used a threshold of the first difference of a spline fit to the FSRsum. Better calibration of the FSRsum, resulting in an objectively determined threshold, would likely improve this component of determining heel strike; if so, placing FSRs underneath the great toe may be able to contribute to the determination of the toe off time. Finally, increasing the data transfer rate of the GaitShoe from 75 Hz would eliminate the need to fit a spline to the FSRsum data, and may also improve the accelerometer and gyroscope data as well.

These initial results demonstrate that the GaitShoe will be an important research tool, capable of enabling the analysis of gait in untraditional ways, such as over long periods of time and in the home environment or through use of pattern recognition, and provides a method for real-time feedback for use in such applications as sports medicine, electro-stimulation, or physical therapy.

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