A Compact Wearable Sensor Package for Clinical Gait Monitoring

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We have developed a compact, wireless, wearable, shoe-mounted sensor package that is designed to provide continuous and real-time monitoring of gait for clinical biomotion analysis. This paper discusses the initial design of our hardware, consisting of a sensor-laden insole and a removable instrumented shoe attachment. Information about the three-dimensional motion, relative position, and pressure distribution of the foot is provided with real-time and wireless transmission of the data from the instrumented shoe attachment to a receiver connected to a nearby laptop or wearable PDA platform. Initial data collection demonstrates the capability of the sensor system to detect different types of gait.

Currently, clinical gait analysis [1] is primarily done in either a motion laboratory, with full analysis of the motion of all body segments using highly accurate optical systems and a precision force-measuring plate mounted on a rigid floor, or in a doctor's office with the physician making visual observations. Analysis in a motion laboratory produces well-quantified and accurate results for gait over a short distance, while the results of visual observations are qualitative and difficult to compare across multiple visits or between differing physicians. However, a dedicated motion lab is expensive to maintain and uses cumbersome equipment attached to the patient, while visual observation is inexpensive and does not require anything to be attached to the patient.

There is thus a need for a low-cost device that can meet the shortcomings of these current approaches, by providing quantitative and repeatable results with minimal imposition on the patient. In addition, there is a need for a device that is capable of monitoring gait over long periods of time and in environments outside of the clinical setting, such as in the patient's home. For example, recent research has suggested that analysis of gait difficulties in Parkinson's patients would be greatly enhanced by studies of gait outside of the motion lab [2].

Over the last decade, a number of systems using non-traditional methods of gait analysis have been developed. For example, real-time pressure analysis at seven locations beneath each foot was provided with an instrumented insole; however this system required the patient to be tethered via power and data lines to the computer [3]. Another group developed a non-tethered insole system and has been able to discern an impressive amount of information about the temporal parameters of gait, such as changes in stride timing, but does not provide real-time analysis [4]. Recently, a non-tethered system with a simply instrumented insole and gyroscope mounted on the shoe has demonstrated the capability of classifying a patient's gait into four different phases [5] and has been used to generate real-time functional electrostimulation that aids in correcting drop-foot walking dysfunction [6].

This research grew out of another on-shoe system, the "Expressive Footwear" project that was worn by dancers who used the movement of their feet to control the music to which they danced [7]. The system consisted of an instrumented insole and compact shoe-mounted electronics, providing a total of sixteen sensed

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parameters per foot (including pressures at various points, position tracking, acceleration and rotation sensing, height measurement, and impact detection). All data was telemetered wirelessly, with 50 Hz full-state updates streaming directly from each shoe. A simple rule-based mapping algorithm controlled the music in real-time. The sensor suite chosen for this device was not optimized for detection of gait features, however, but rather designed to allow a performer to explicitly control a musical stream.

These and many other systems [8] have been able to provide detailed and useful data representing some aspect of gait. The goal of our research is to be able to completely characterize the motion of the foot for clinical applications, sensing all parameters that could be of interest to the biomotion community. In addition, we will provide the data in real-time, so that it can ultimately be used to give prompt feedback to the user via interactive therapy.

Methodology

Hardware Development. In collaboration with our colleagues at the Massachusetts General Hospital (MGH) Biomotion Laboratory [9], we determined the following important top-level functional requirements for our device, the Shoe-Integrated Gait Sensor System (SIGSS):

1. Attach removeably to the subject’s own walking shoes.
2. Effect no change in gait.
3. Characterize the motion of both feet.
4. Communicate and transmit the data wirelessly.
5. Provide validated kinematic data & analysis in real-time.

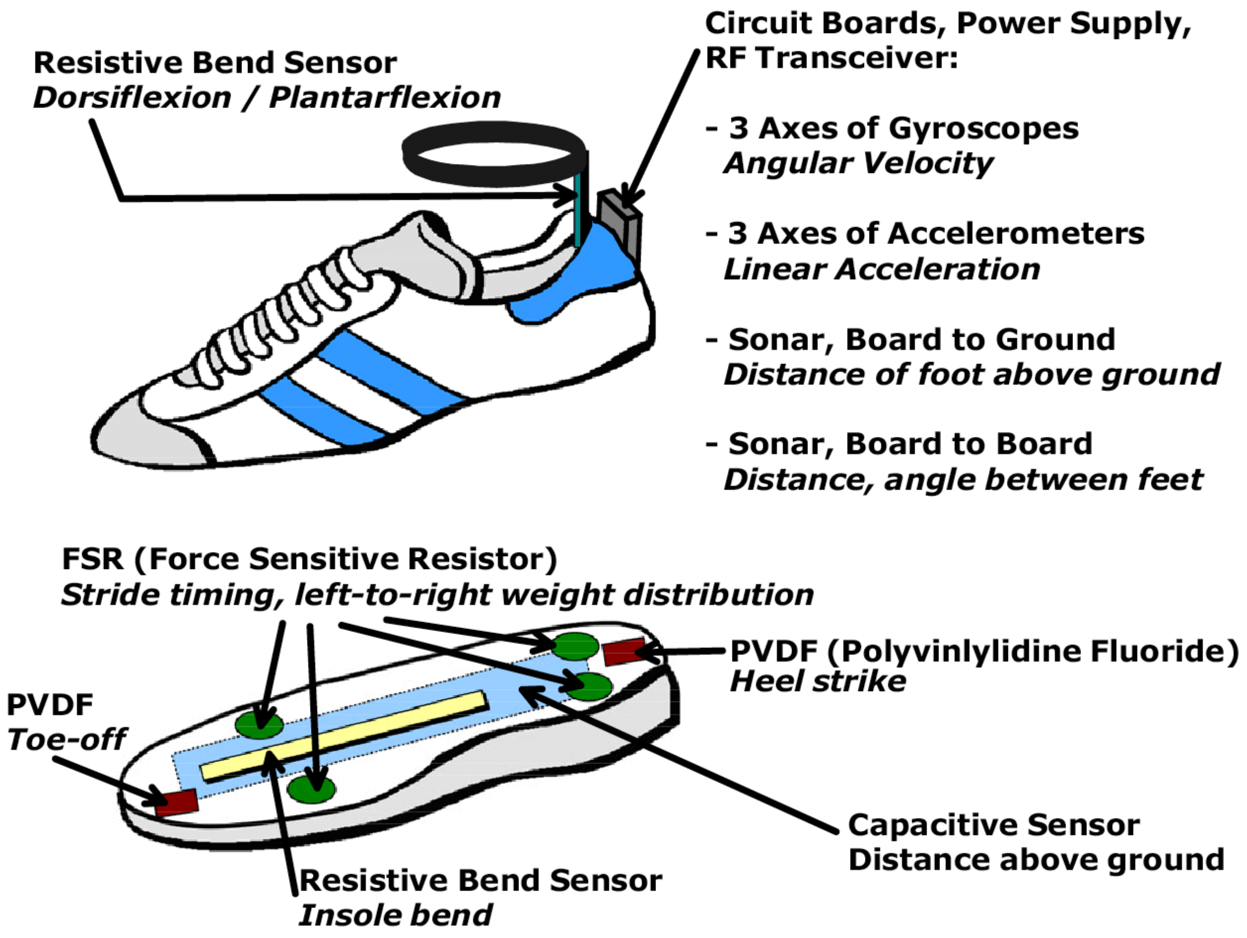

Figure 1: Schematic of the Shoe-Integrated Gait Sensor System (SIGSS)

Fig. 1 shows a schematic of the SIGSS, and Fig. 2 shows photos of the initial prototype as mounted on a sneaker. The instrumented insole (Fig. 2, left) is placed inside the patient's shoe. Laminated between two 0.02 inch sheets of clear Type 1 PVC (polyvinyl chloride) heavy-duty film sheets are the insole sensors: four FSR pads (force sensitive resistors that measure continuous pressure), two PVDF strips (polyvinlylidine fluoride, a piezoelectric material that measures dynamic pressure), and two pairs of resistive bend sensors. The FSRs provide a coarse measurement of the pressure distribution beneath the foot, and are placed with two beneath the heel (medially and laterally) and two located forward, behind the toes (one beneath the first metatarsal head, and another beneath the fourth and fifth metatarsal head). The PVDF strips provide dynamic information about “heel strike” and “toe off,” and are located beneath the heel and beneath the hallux (big toe). Each pair of bend sensors provides information about bi-directional bend (each pair consists of two bend sensors which are placed back to back). One pair provides information about the extent of plantarflexion or dorsiflexion at the ankle, hence is located at the back of the shoe and inserted into an ankle strap so that it bends around the rear edge of the shoe as the ankle tilts. The other pair of bend sensors provides information about the extent of plantarflexion or dorsiflexion at the metatarsals during walking, and thus is located at the forward portion of the insole.

Figure 2: Photos of the first prototype of the SIGSS – insole (left) and shoe with electronics (right)

The shoe attachment (Fig. 2, right, mounted at the heel) contains three stacked circuit boards, the power supply (currently a 9V battery), and the antenna for wireless transmission. The mass of the current prototype is approximately 200 g. As depicted in the close-up photo of Figure 3, the circuit boards are modular components designed to be stacked atop each other (mating via a pair of commonly-placed connectors), thereby allowing a custom compact sensor system to be easily configured for various applications [10]. The three circuit boards in the system of Figure 2 each address specific needs: one contains the conditioning electronics for the insole sensors, a second has the microcontroller that collects data from the other boards together with the wireless transceiver, and a third is a compact inertial measurement unit (IMU) that has a full set of three gyroscopes and three accelerometers to measure angular velocity and linear acceleration about three axes. Any redundancy in these measurements will be used to improve detection and reduce errors. A fourth board now in final development will provide capacitive sensing to measure the height of the shoe sole above ground, a sonar to measure the distance to the ground from the heel, and another sonar for measuring both distance and angle between shoes. Details are given in [8]. A simple TDMA scheme allows both shoes to share a single RF channel; the embedded transceivers on the SIGSS processor card are capable of operating at 115 kbps, allowing all 18 parameters from both shoes to be updated at better than 50 Hz. As the net average current draw of this system is of order 50 mA, the life of a standard 9V alkaline battery extends significantly past a half day of continuous operation, providing ample data for analysis and diagnosis, and therapy.

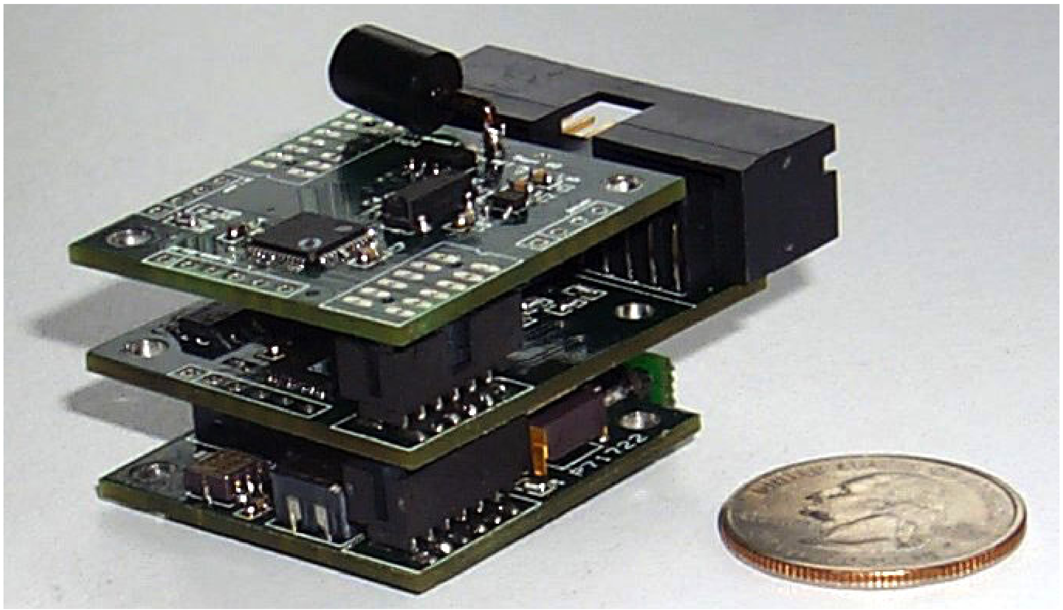

Figure 3: Close-up photo showing the stacked sensor architecture used to instrument the SIGSS

Signal Analysis. Initial results obtained with the prototype system are shown in Fig. 4. Current work is focused on the development of methods to analyze the data, including calibration and analysis of the outputs of the sensors, as well pattern recognition methods [8] that can extract clinical gait-relevant features. A visual inspection of these plots, however, as described below, suggests that the many degrees of sensing freedom encompassed in our device should be able to easily distinguish between the different types of walks shown in the test examples of Fig. 4. Note that these plots don't include any data from the insole bend sensor, as it was being redesigned at the time, and from the sonar and capacitive sensors, as they are currently nearing completion and weren't yet ready for this test.

Discussion

The initial results shown in Fig. 4 visually demonstrate the capability of this system to detect changes in the foot motion during different types of gait. Data are shown for one foot only. In 4a, the subject was told to walk normally; in 4b, to walk quickly; in 4c, to shuffle her feet, and in 4d, the subject was given a wine glass filled with water and was instructed to balance it on the palm of her hand while walking.

Comparing 4a and 4b, the sensor outputs have nearly identical patterns, but at different frequencies, as expected from the increase in walking speed. Comparing 4c and 4d with 4a, however, the changes are striking. In 4c, the two heel FSRs exhibit relatively flat signals (indicating that little weight was put on the heel), while the profile of the front FSRs are quite different (indicating a different emphasis near the toes). The "gyro z" output and the ankle bend are also both flattened, indicating very little flexion at the ankle during the shuffling gait. In 4d, the frequency is slowed, and the outputs are much smoother, suggesting a careful and deliberant motion.

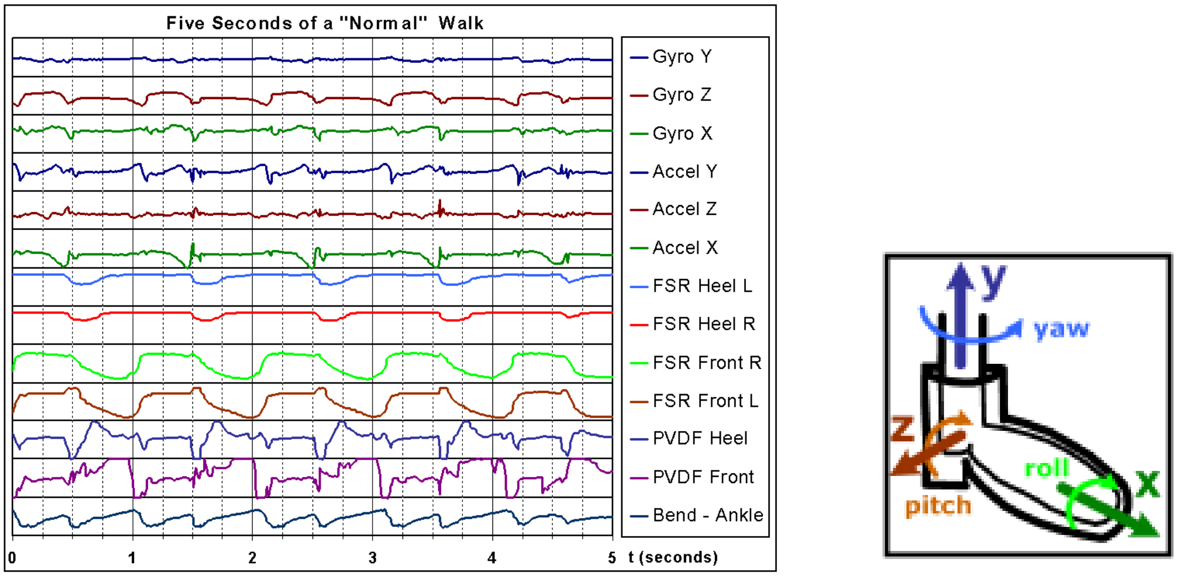

Figure 4a: Initial results obtained with SIGSS (Normal Gait) and shoe-fixed coordinate axes (right)

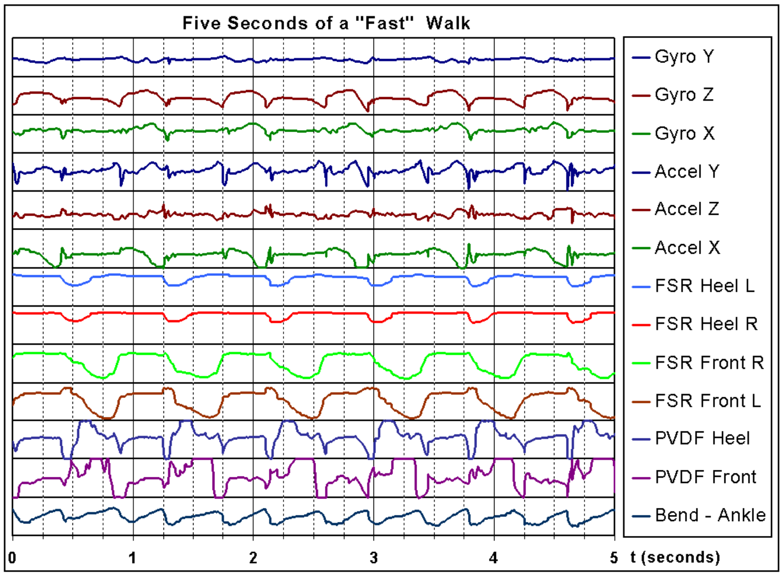

Figure 4b: Initial results obtained with SIGSS (Fast Walk Gait)

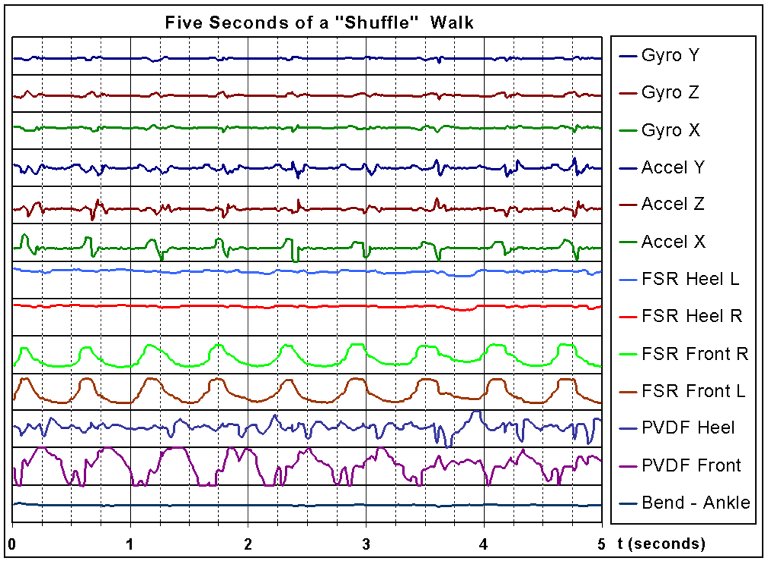

Figure 4c: Initial results obtained with SIGSS (Shuffle Walk Gait)

Figure 4d: Initial results obtained with SIGSS (Gait while Performing a Difficult Task)

Conclusion

There is a clear need for a device which is capable of inexpensive yet quantitative analysis of gait in environments other than the traditional motion lab or physician's office. While our work is still in development, the initial results show significant breadth in measurement capability and indicate that it will make many useful contributions to clinical gait analysis. We are currently finalizing a second-generation prototype and are working on analysis methods for the data. After these are implemented and validated with the commercial gain-measuring equipment at the MGH Biomotion Lab, we will use our device to look at gait in different environments and at differences between the gaits of various subjects, also exploring the possibility of using our derived features for real-time interactive therapy, perhaps with a sonified musical stream, such as explored in our previous interactive dance project [7].

Both the Expressive Footwear [7] and the system described in this paper are examples of dense wireless sensor clusters that sense many different general parameters, as opposed to the more standard approaches that concentrate on making good measurements of only a few particular degrees of freedom. Taking a hunting analogy, one can think of our approach as capturing many phenomena with a wide shotgun, rather than going directly for a particular signature with a sharpshooting rifle. Although the narrower approach generally guarantees a particular result, a broad sensor suite enables one to catch many features through appropriate fusion algorithms, robustify the detection by comparing signatures across different sensor families, and supports many different applications that look at the data in different ways. As Moore's Law and its corollaries enable sensors to approach commodity (becoming smaller, less expensive, and much easier to integrate) we expect that this strategy will become common in many products and devices.

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