Design and Characterization of Shoe Embedded Pressure Sensors for Gait Analysis and Rehabilitation

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1 Background

In clinical gait therapy, the quality of gait analysis is critical for developing a training plan and monitoring patient progress. Ground contact forces (GCFs) are often recorded to estimate joint torques which can quantify a patient’s needs and strength development. They are also useful in designing and controlling rehabilitative and assistive devices. In clinical gait analysis, force plates are used to measure GCFs objectively and precisely [1, 2]. Currently, forces sensitive resistors (FSR) are often used as a mobile platform to measure GCFs. FSR based platforms exhibit considerable hysteresis and have low durability, some requiring replacement after only 5-hour long uses. As an alternative to FSR, a pair of sensor-embedded shoes (smart shoes) relying on air pressure sensors has been presented in previous research [4]. Some details regarding the precise characteristics of the sensing abilities were unknown, though, generating unanticipated errors during use.

In this paper, the sensing units of wireless smart shoes are characterized and tested to verify their capability to provide real-time and accurate GCF measurements. For the prototype, silicon tubes were sealed on one end, wound into coils, secured to the underside of the shoe’s insole at four points of interest (heel, toe, the first and fourth metatarsophalangeal joint) routed outside the shoe, and their open ends are connected to air pressure sensors as shown in Fig. 1(a). The pressure sensors were placed on a circuit board along with a battery and microcontroller responsible for reading sensor outputs and wirelessly communicating data to a nearby device, as shown in Fig. 1(c). The sensing unit on the lateral side of the shoe is 1.2” x 1.3” x 3.95”. A series of calibration tests were first performed on the tube-insole subsystem in isolation to test linearity, repeatability, and hysteresis. Then practical experiments were performed on a healthy subject to determine the accuracy of GCF measurement. A previously presented hysteresis filter was implemented in practical testing [3].

2 Method

In previous work, the coils of the tube placed on each shoe’s insole was coiled manually. In this work, the shoe’s tube was coiled utilizing a 3D printed mold, shown in Fig. 1 (b), which reduced the manufacturing time of an insole from one week to one day. NXP MPXV7025 series pressure sensors were used to read tube pressure, and an Intel Edison module, powered by 9 V battery, was used for sampling, signal processing, and wireless communication at 100 Hz utilizing Bluetooth Low Energy (BLE) protocol. The configuration offers greater processing power and communication capability than previous versions [1].

To verify the new design, calibration was performed on the tube-insole subsystem in isolation. A Digilent Analog Discovery was used to measure pressure sensor output and applied load in synchrony. An Instron 5944 material testing machine was used to apply controlled compressive force on the tube coils mimicking human loading. Experiments were performed to inspect the linearity of the sensors’ response, hysteresis effect, and repeatability of the system. Results from the linearity testing were used to develop a relationship between sensor output and applied load that was later used in practical testing. Linear regression method was used to fit the data and build the model.

To measure hysteresis effects, cycles of loading and unloading were conducted at rates from 50 N/s to 800 N/s. To test the design’s repeatability, 1000 load cycles were applied to the system. In each cycle, the load began at 0 N, was increased to 800 N in one second, brought back to 0 N in one second, then let to rest at 0 N for 0.5 seconds.

Two practical experiments were performed on a healthy subject, age 19, (5’ 10”, and 120 lb.). In both experiments, GCF measurements were taken from the shoes and a force plate in the treadmill. In the first experiment, the user stood on the treadmill for one minute. In the second, the user walked on the treadmill for three minutes at 1.4 mph. Each experiment had three trials.

3 Results

Results from linearity testing reflect that the average sensor output-applied force relationship of 2.59 mV/N is found with y-intercept 2.22 V. The 0.98 R-square value for this linear regression model suggests it is reasonably accurate.

Fig 2 displays the results of hysteresis effect testing. It shows that an increase in loading rate magnifies hysteresis effects. The previously designed hysteresis compensator demonstrates effective hysteresis reduction [3].
Repeatability testing results are shown in Fig. 3. Repeatability performance is defined as the absolute value of the difference between the final and initial y-intercept values over the initial one. As cycles progressed, there is noticeable drift between calculated load and applied load. Further testing reveals that this is not due to air leakage, as is originally hypothesized, but due to the material characteristics of the silicone tube. Comparison between silicon with durometers 35 and 50 mm shows that repeatability improves with higher material stiffness.

For the standing experiment, the estimated total GCF is calculated by summing smart shoe sensor measurements for raw and filtered data, and then compared with force plate load values. For the walking experiment, the right and left shoes’ sensors are summed independently and compared to their corresponding force plate’s measurements. The root mean square error (RMSE) between shoe and force plate data is used to compare results. Both of experiments’ results are shown in Table 1. The mean value of total GCF from raw data, filtered data and force plate measurements are 663.7 N, 541.5 N and 555.2 N respectively. Some results from the left foot in walking experiment are shown in the Fig. 4.

4 Interpretation

With calibration and practical tests complete, the sensors’ performance was characterized. A linear function between applied forces and sensor output signal was found while the hysteresis of the system was minimized by applying a filter. It was observed during the repeatability test that the zero-load voltage decreased with number of load cycles. A detailed study on the material properties of the silicone tube will clarify this shift. The comparison of the RMSE values between raw and filtered data from the shoes indicated the improvement of the GCFs measurements. The shoes can serve as an affordable, mobile gait monitoring platform for use in homes as well as hospitals. Future work will focus on implementing the shoes in a clinical setting. The direct next step is to develop data processing algorithms to identify patients’ rehabilitation progress from shoe measurements. In broader horizons, the shoes could be applied to examine an athlete’s gait, function in virtual or augmented reality systems, or assist in controlling assistive robotic devices [5].

Acknowledgement

This research was partially supported by Fulton Undergraduate Research Initiative (FURI) at Arizona State University (ASU). The authors would like to thank Professor Panagiotis Polygerinos at ASU for his help in calibration.

References