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

Design and Development of a Cost Effective Plantar Pressure Distribution Analysis System for the Dynamically Moving Feet

R. Karkokli, Member, IEEE, K.M.Valter McConville, Ph.D., Member, IEEE
Ryerson University, Toronto, ON

Abstract – This paper portrays the design and instrumentation of a low cost plantar pressure analysis system, suitable for clinical podiatry. The system measures plantar pressure between the foot and shoe during dynamic movement in real-time, which can be used in clinical gait analysis. It contains a pressure sensing insole which the patient can insert in his/her shoe, and user-friendly software to graph and analyze the data. Applications include occupational health and safety, research and private practice.

Key words: Biomedical, Foot/Plantar Pressure, Flat Feet, Pressure Sensors, Gait, Measurement Systems.

I. INTRODUCTION

The feet are the foundation of the human body. They provide stability and support while standing, walking, and running. However, the condition of flat feet is a very common biomechanical gait abnormality that causes problems during these everyday activities. In this condition, the patient's arch collapses due to the unbalanced body weight distribution along each foot. This arch is in essence a gap that is located between the inner side of the foot and the ground as the patient is standing, which provides stability and balance to the legs in static and dynamic motion in order to evenly distribute the weight of the body on the feet and knees. However, suffering from an abnormality in the shape of this arch causes biomechanical problems that lead to an imbalance in the patient's alignment which in turn results in foot, ankle, knee, leg, hip, and/or back pain.

This biomechanical problem is rarely a hereditary problem. Possible causes could be that the patient is suffering from diabetes, peripheral neuropathy, or various musculoskeletal, integumentary, or neurological disorders.

In order to solve this dilemma, orthotic insoles are custom designed and made for the patient to fix the curvature of the arch of each foot by providing it with proper support. Traditionally, orthotic insoles are made using casts in which the patient would have to stand on to create an impression of the feet to duplicate any misalignments, and then the cast is sent to the laboratory to correct these misalignments with compensation and stabilization techniques. However, this type of technique is not sufficient, since having flat feet is a problem during walking or running, not just standing. Up to three times the body weight is placed through each foot during the running process. Therefore, a system needs to be developed in order to closely measure and analyse the pressure distribution along each foot during dynamic movements of the feet. This can be done using a computerized system that provides the podiatrist with the information needed in order to understand each patient's problem precisely and create an insole that best fits the patient's needs by the use of advanced timing and graphing tools.

There are a few computerized solutions in the market, including pressure sensing boards and walkways. The way these pressure sensing boards work is that the patient is required to walk and land with the same foot three times and repeat for each foot. The system then takes the average of each foot and graphs the obtained data in a 2-D and 3-D showing the different pressure regions along each foot. However, since this method takes the measurement of a slow walking movement of the patient it does not give a good picture of where the pressure regions are concentrated and how intense they are in those regions since each person's walking pace varies. Another limitation to this technique is very that the pressure is intensely concentrated during the running process and running data is not practically obtainable with this system.

Pressure sensing walkway systems are probably a better solution when compared to the pressure sensing board since they can monitor the dynamic motion of both feet at the same time, however, they maybe very expensive since they use a large number of sensors to make the walkway long enough for a patient to run a small distance.

Clinical insole based plantar pressure systems have been developed and used in the analysis of paediatric gait abnormalities such as in cerebral palsy. Additionally, foot pressure and motion detectors have been implemented as advanced body position sensors in advanced computer systems research. These systems are more sophisticated and expensive than what is required by many applications such as podiatry or virtual reality research.

This research project is a cost effective system that measures different pressure regions along the dynamically moving feet using pressure sensing electronic insoles that the patient can insert in his/her shoes and walk or run for a period of time to provide the required information. The obtained data is displayed after averaging the acquired data to provide the user with the pressure profiles of the left and right foot along with dynamic weight transfer and local pressure concentrations to assist in writing proper orthotic prescriptions.

II. DESIGN DESCRIPTION

The system requirements were defined based on the podiatry application. The selection of the sensors was the main key driver of the system design. Excitation and/or signal conditioning circuits are almost always needed to interface the sensor and provide adjustable calibration, amplification, linearization, and level transformation functions. There are many different types and technologies of pressure sensors, however, thin piezoresistive pressure sensors, *FlexiForce®*, were used in this research project.

Piezoresistive pressure sensors provide an analog output signal that is proportional to the input pressure. The typical full scale span for this type of integrated sensor is 100 mV which is sufficient for many applications. However, in this project the sensors' output was filtered using a low pass filter, and amplified in order to obtain the required results.

The ultra-thin *FlexiForce®* sensors that were used are versatile, durable piezoresistive force sensors which act as a force sensing resistor in an electrical circuit. They provide an output voltage reading that is proportional to applied force. At zero load conditions, the resistance of these sensors is very high (>5MΩ). When a force is applied, the resistance decreases as it can be observed from Figure 1 below in which it shows the Force vs. Resistance and Force vs. Conductance(1/R) characteristics of the *FlexiForce®* sensors. Since the conductance curve is linear, it is very useful in calibration.

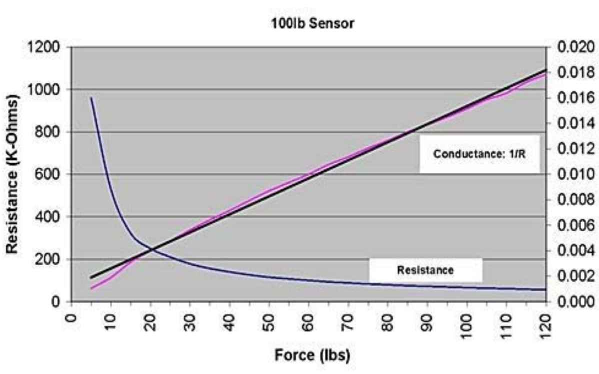

Figure 1: Force vs. Resistance and Conductance Relationship

Each electronic insole was made out of two layers of two foam non-static layers, one on top and the other on the bottom in which the sensors were placed.

For simplicity, a Data Acquisition (DAQ) card was used instead of a microcontroller. The basic block diagram of this system is shown in Figure 2.

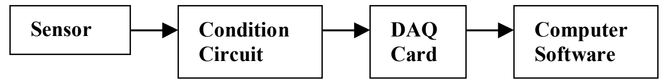

Figure 2: System's Block Diagram

Information from the sensors is sent to a signal conditioner integrated circuit for compensation and amplification. The results are then sent to the DAQ card which has an A/D converter to digitize the analog voltage data obtained from the sensors. These data are then interfaced to the PC through the USB interface of the DAQ card. In addition, a user friendly software program was established in LabVIEW to read the acquired data from the DAQ card and perform the required calculations and averaging, then provide a graphical representation of the manipulated data for a better understanding of where most of the pressure is applied along each foot.

Hardware Design:

Eight sensors were used in this project. A research was conducted in order to find the best placement for each sensor along the foot to get the best results when interpolation is applied. Figure 3 shows the layout of the sensors in which two sensors are placed on the heal area, three sensors along the length of the arch of the foot, two sensors on the front of the foot plus one sensors on the big toe.

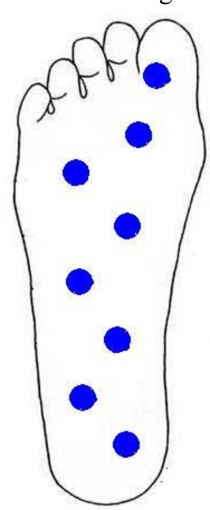

Figure 3: Placement of the sensors on each foot

The sensors initially read up to 100lb, and it was required to increase that range to 200lb. The circuit in Figure 4 was used to achieve that requirement. As mentioned before, the sensor's resistance (Rs) is more than 5MΩ at no force condition, and it decreases with the increase of the applied force. From the gain formula, it can be said that decreasing the sensors resistance (Rs), and increasing the feedback resistance (Rf) would increase the output gain. Moreover, the feedback resistor was decreased to obtain the required force range (0-200lb). When Rf is decreased, the sensitivity is decreased and therefore the force range increase. This approach also solves the problem of saturation in which the sensors output would no longer vary with the applied force when the force limit is crossed. In addition, it was important to limit the current to a maximum of 2.5 mA as that is how much the sensors can handle.

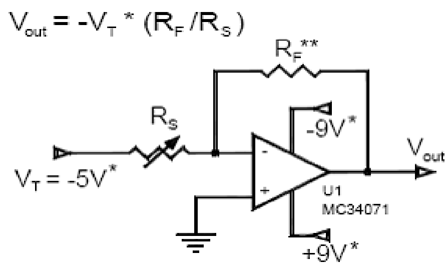

Figure 4: Sensor Excitation Circuit

Conditioning of Sensors:

Each sensor was required to be conditioned before calibration and testing in order to provide accurate results. This was done by applying 110% of a test weight within the range for a couple of times and letting the sensor to stabilize. Moreover, the interface (foam plates that protects the sensors from sheer force effect) between the sensor and test subject material used was the same during conditioning as during calibration and actual testing.

Calibration of Sensors:

To calibrate the sensors, a load that is approximately the applied load during testing and system use was applied evenly, and the output of the above circuit was recorded five times for five different forces or weights. However, since it was required to get a linear relationship between the applied force and the output voltage, the sensitivity was changed each time to obtain this linearity and the above approach was repeated for each sensitivity value, or the feedback resistor value (Rs), until a close approximation of linearity was obtained. This was repeated for each sensor separately.

Software Design:

Real-time Reading of Sensors:

Each sensor's output is connected to an analog input channel in the DAQ card which transfers the information to the computer. Using LabVIEW, each sensor's circuit output is read continuously at a sampling rate of 500 samples/s using a while loop that stops when the user hits the stop button. Each physical channel that corresponds to the individual eight sensors is connected to a low pass filter before it enters the while loop. Moreover, the program displays the final averaged value of each sensor's output after converting its voltage value to an equivalent pressure value. Since there are only eight sensors available, interpolation and filling in the missing data was required in order to obtain a meaningful presentation of the results. This was done using Matlab tools.

Memory management:

Real-time reading of sensors requires a large memory space. However, in order to save memory, the output readings of each sensor were averaged with the previous reading in a loop until the user presses a stop button. The results will give the final averaged value of each of the eight sensors in an array which can be stored and graphed later.

Sample results are shown in Figure 5 below, which shows that there is more pressure applied to the toes and front of the foot compared to the rest of the foot.

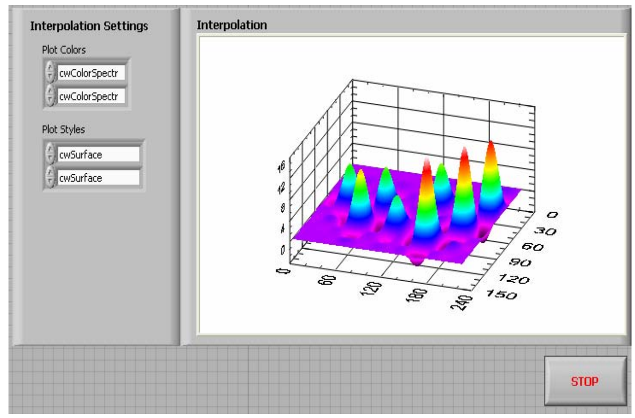

Figure 5: Sample results

III. APPLICATIONS

This system is ideal for plantar pressure analysis. It could be used as a cost effective alternative by podiatrists to diagnose flat feet and prescribe an orthotic insole that is custom made for each patient based on his/her condition and needs. This system identifies the pressure profile discrepancies across the foot and between left and right foot. It reviews the dynamic weight transfer and local pressure concentrations. It can also be used to monitor improvements in balance and sway, strength and weight bearing problems as they respond to treatment. Moreover, the dynamic foot pressure present in this system can be used to predict and manage aid by determining the specific areas under the foot that are prone to ulceration which is a form of diabetic neuropathy, and also in arthritis detection. Additionally, many interesting applications are possible in research. Virtual Reality systems are integrating sensory and motor data from the entire body. This system could serve as an additional source of data.

IV. FUTURE WORK

The system has been developed with preliminary tests for proof of concept. Further testing will be required to determine the system performance characteristics. Application specific development will then be possible. Future work includes the further development of the user interface based on user feedback. Additional modifications could include a wireless connection, and additional sensors for a higher resolution of the patterns of plantar pressure.

V. ACKNOWLEDGEMENTS

The authors would like to acknowledge Wisam Aldabbagh and Rohit Narula for their help and support in this project.

VI. BIBLIOGRAPHY

1. Woodward, S. and Wojslaw, C. Sensor Circuits and Digitally Controlled Potentiometers. Intersil Application Notes AN135.0, May 4, 2005.
2. ________ . FlexiForce® Sensor User Manual Rev. F. Tekscan, Sept. 23, 2005.
3. Soames, R W. Foot Pressure Patterns During Gait. J Biomed Eng. 7(2): pp. 120-126, 1985.
4. Pierce, S., Johnston, T.E., Smith, B.T., Orlin, M. and McCarthy, J.J. Effect of Percutaneous Electrical Stimulation on Ankle Kinematics in Children with Cerebral Palsy. IEEE Bioengineering, Proceedings of the Northeast Conference, pp. 81-82, 2002.
5. _________ . Low Cost Multifunction DAQ for USB, National Instruments® , 2005.
6. Paradiso, J.A. Hsiao, K. Benbasat, A.Y. Teegarden, Z. Design and implementation of expressive footwear. IBM Systems J., 39(3-4), pp. 511-529, 2000.
7. Morris, S.J and Paradiso, J.A. A Compact Wearable Sensor Package for Clinical Gait Monitoring. Offspring, Motorola. 1(1), pp. 7-15, January 31, 2003.
8. Abu-Faraj, Z.U., Harris, G.F., Wertsch, J.J., Abler, J.H. and Vengsarkar, A.S. Holter System Development for Recording Plantar Pressures: Design and Instrumentation. IEEE. pp. 934-935, 1994.
9. Femery, V., Moretto, P., Hespel, J.M. and Lensel, G. Plantar Pressure Biofeedback Device for Foot Unloading. Proc. 5th Symp. on Footwear Biomech. Zurich, pp. 36-37, 2001.