A PORTABLE FOOTSWITCH SYSTEM: DESIGN AND IMPLEMENTATION

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Abstract. *This paper describes the development of a compact footswitch system. It was designed to acquire and transmit information from the patient's feet to a host computer. There, the therapist can observe, save and measure time between some selected events during the patient's walk. The developed footswitch system can be divided into two main blocks: footswitch device - sensors under the patient's foot and the microcontrolled CPU, and the host where a friendly software interface allows different measurements of the acquired data. Under each foot of the patient there are four pressure sensors in specific positions: calcaneus, head of fifth metatarsal, head of first metatarsal and first phalange (toe). During a planned walk, pressure data are acquired from both feet of the patient, sent to the host computer for different measurements. Before the measurement, some patient data (name, age, mass, height) must be informed. One of the main measures is the time that is relevant to the toe-off point of the pre-swing phase and included the initial contact phase of the gait cycle. The Polytechnic Institute and the Biological Sciences Institute of PUC Minas carried out this multidisciplinary research to design and evaluate this first version of the assisting device for clinical evaluation of rehabilitation techniques for orthopedic pathologies. Using the footswitch system, the retest reliability of the temporal and distance parameters of gait was investigated within sessions for stroke patients in the early stage of rehabilitation.*

Keywords*: footswitch, orthopedic, rehabilitation*

1. INTRODUCTION

The increasing longevity and the consequences of aging already worry researchers around the world. In 1980, the population of old people in Brazil was approximately 7 million. In 2000, this value reached a number of 14 million aged Brazilians from a total population of 179 million. One of the most severe pathology associated to aging is the breaking col of femur. It is estimated that 30% of aged adults will suffer hip breaking, leading to incapacities such as loss of mobility and death (Birge *et al.*, 1994). 80 to 90% of hip breakings results from falls, mainly during a simple walking. So the alterations to walking standards have been claimed as factors that contribute to falls in aged people (Kerrigan *et al.*, 2000).

The study of the manner of walking is a quantitative description of the locomotion that allows visualization, quantification and evaluation of the body locomotive system (Allard *et al.*, 1995). It was already demonstrated that the secular and space walk data reflect the locomotive function of the patient. Some studies cite the secular and space variable data as important alterations in the walk of aged (Grabiner *et al.*, 2001). The secular data of the walk include time measurement of: support phase, oscillation phase, double support phase, and speed of the walk. The spatial data are: the length of the step, cadence - number of steps per minute, size of the support base and the areas of contact of the foot with the ground (Amadio *et al.* 1999; Winter, 1991). Therefore, the secular and space variable are important to indicate the state of the locomotive system of the patient when compared with normal values (standards) being used to evaluate the treatment (Õunpuu, 1995).

In this paper we present a microcontrolled system to acquire and send force/pressure data from the foot of the patient to a host computer. This system is called footswitch. Four pressure sensors are placed below each patient's foot in some specific regions: calcaneus, head of fifth metatarsal, head of first metatarsal and first phalange (toe). The

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force/pressure is acquired, digitalized and sent to a host computer by a serial link, where different time analysis can be realized by the therapist. By using such device, it is possible to get a precise measurement of spatial data. During the specification of this device, it was necessary a close relation between the engineering and physiotherapy students. Students of the Electronics and Mechatronics Engineering of PUC Minas carried out the design, implementation and lab evaluation of the device. The main goal of this project is a close cooperation between the Engineering and Physiotherapy Undergraduation Courses at PUC Minas. This relationship allows projects developments about these areas, making possible the development of measurement devices to study abnormalities of the movement allowing adjusted therapeutically behaviors. This paper focus on the design, implementation and calibration of the footswitch, as will be presented in the next sections. Future works will present the use of the developed device by the physiotherapy professionals.

2. HARDWARE DESCRIPTION

The footswitch was implemented using a microcontrolled (PIC16F877 Data Sheet, 2001) data acquisition interface as presented at Figure 1 (Tocci, 1983). Electronic signals from force sensing transducers are driven to the microcontrolled board, where an analogue to digital converter, built in the microcontroller, generates digital words. The microcontrolled was programmed as an embedded system to do the signal acquisition on a constant frequency - 50 hz (Embree, 1991). Then, it transmits the data through the serial port to a personal computer, the host. On the host computer, the generated database can be analyzed and processed by the developed software interface.

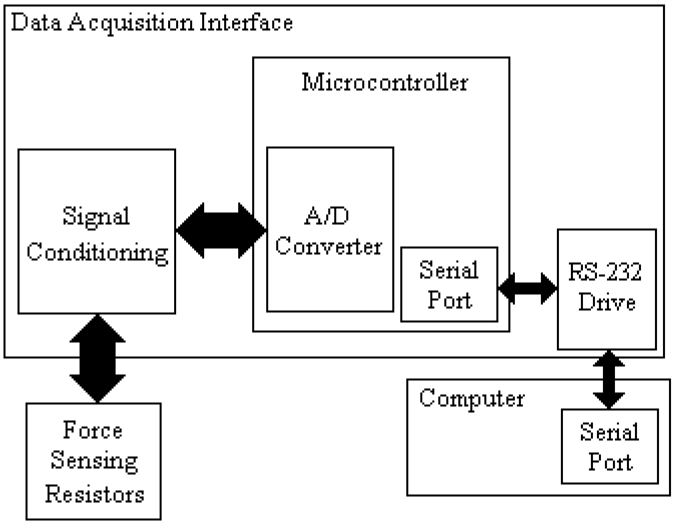

Figure 1. Hardware Block Diagram.

Eight force sensing resistors (FSR), are distributed on a insole pair, working as force/pressure sensors. The force sensing resistor is a polymer-thick film device, which exhibits a decrease in resistance with an increase in the force applied to the active surface. If no force is applied, the sensor resistance is high, more than 100 kohm. This value decreases as the force applied increases. When saturated, increased forces will not cause resistance changes. The sensors on footswitch are located under a patient's foot. When the patient touches the floor, the charge in the FSRs is sufficient to saturate them. When the floor is not being touched, the charge on the sensors is minimum and then their resistance is maximum. On these conditions, the system can tell if the patient is touching the floor or not.

The signal conditioning is performed in the circuit shown in figure 4 of section 3.3. Using that circuit, increasing forces on the FSR surface results on increasing output voltage levels. If the force is applied on the sensor, its resistance decreases and the potential in the non-inverting input of the amplifier becomes higher, driving the output of the circuit to a higher level.

During the sampling process, it is used an anti-aliasing filter to cut undesired frequencies of overlapped signals to the original signal. This is a low pass filter with high attenuation in the cut-off frequency. This filter should follow the Sampling Theorem, which says that its cut-off frequency is half the sampling frequency. The Footswitch uses a seventh order elliptical filter to accomplish these requirements.

The analogue to digital converter, incorporated to the microcontroller, has eight multiplexed channels. Each filter output is connected to one of these channels. The channel selection is implemented by firmware – embedded software. In a fifty times per second frequency, data is acquired sequentially from the eight channels and then transmitted through the serial port to the host computer. There, the data is saved on a file as a nine columns matrix, corresponding to the time value and the eight analog channels. The number of rows is a function of the acquisition time. Finally, this file is loaded in the developed software for analysis and information processing.

3. DEVICE CALIBRATION

In order to evaluate the precise answer of the developed device, some procedures were implemented. They are the mass calibration and the sensor-electronics calibration. It was necessary to calibrate the mass, and then evaluate the output characteristics of the electric resistance of the FSR. It was also necessary to determine the uncertainty of the force reading in order to evaluate the system performance.

3.1. Mass Calibration

Initially, it was implemented the calibration of the masses used to evaluated the sensor response (Dieck, 1997). Ten different masses of approximately 100g were used. The weight of the masses was measured using a “Balança Digital BG”. Its characteristics are:

- Manufacturing: Indústria e Comércio Gehaka Ltda;
- Model: BG2000;
- Maximum weight: 2020g;
- Operation temperature: 0 to 40^{o}C;
- Resolution: ±0,01g;
- Thermal derive: ±4x10^{-6} g/^{o}C.

Glasses protected the balance plate in order to avoid wind influence. The procedure was repeated 15 times for each measured value. For each measurement it was realized the tare of the balance. The ambient temperature was controlled at 25 ^{o}C. It was computed the influence of the temperature in the final result using the thermal derive.

Table 1 presents the results of the measurements for the values from 100g to 1000g. The measurement result (MR) is composed of three parts, as shown in the below equation (Gonçalves, 2002):

$$MR = IA - C_c \pm U_{95\%} \ , \tag{1}$$

where *IA* is the indication average; C_c is the combined correction attributed to the systematic error and subtracted from the average; and $U_{95\%}$ is the expanded uncertainty with 95% probability that comes from the random errors. Its value is written as:

$$U_{95\%} = k_{95\%} U_c \ , \tag{2}$$

where U_c is the combined uncertainty. The value of the abrangence factor $k_{95\%}$ is tabled, and it is a function of the degree-of-freedom effective ν_{ef}, that is written as:

$$\nu_{ef} = \frac{u_c^4}{\left(\frac{u_1^4}{\nu_1} + \frac{u_2^4}{\nu_2} + \ldots + \frac{u_p^4}{\nu_p} \right)} \ , \tag{3}$$

where are known the values of the components uncertainties, u_p, and its respective degree-of-freedom and combined uncertainty, ν_p.

Below it is presented the uncertainties sources and an estimative of the random and systematic effects on the mass calibration shown at Table 1:

1. Indication repeatability – Re – It is a random effect with a normal distribution and 14 degrees-of-freedom.
2. Resolution – Re – It is an error from the numerical approximation. It is also a random error and has a normal distribution with center in value 0. The extreme values are half the resolution (-R/2 and R/2). It this experiment they are –0,0050 and +0,0050. For this uniform distribution, which divisor is $\sqrt{3}$, the combined uncertainty of this source is ±0,00289g. Its degree-of-freedom is $\nu = \infty$.
3. Thermal derive – DTer – Knowing that the balance calibration was executed at 20^{o}C (balance calibration certificate) and the measurements were realized at a higher temperature environment, it is introduced a uncertainty component or error on the measurements presented by the balance (weight device). The variation of the environment temperature has two components: one systematic and one random. The random component is modeled as a normal distribution of the results, centered in zero, with limits

informed by the manufacturer (±4x10^{-6}g). For this uniform distribution, whose divisor is $\sqrt{3}$, the combined uncertainty of this source is ±2,3094 x10^{-6}g and its degree-of-freedom is $\nu = \infty$.

Table 1. Measurements Results and Uncertainties.

Mass	1	2	3	4	5	6	7	8	9	10
IA [g]	99,9026	99,6673	99,6653	99,2300	99,5233	99,7680	99,0420	100,1873	99,2233	98,9960
Re [g]	3,44E-3	1,53E-3	1,65E-3	2,18E-3	2,87E-3	2,79E-3	3,68E-3	2,48E-3	2,11E-3	3,63E-3
ν_p	14	14	14	14	14	14	14	14	14	14
R [g]	0,00288	0,00288	0,00288	0,00288	0,00288	0,00288	0,00288	0,00288	0,00288	0,00288
DTer [g]	2,31E-6	2,31E-6	2,31E-6	2,31E-6	2,31E-6	2,31E-6	2,31E-6	2,31E-6	2,31E-6	2,31E-6
U_c [g]	6,34E-3	4,42E-3	4,54E-3	5,07E-3	5,76E-3	5,68E-3	6,57E-3	5,37E-3	5,00E-3	6,51E-3
ν_{ef}	159,96	969,99	799,10	408,42	226,56	239,58	142,34	307,16	442,08	145,98
$K_{95\%}$	2	2	2	2	2	2	2	2	2	2
$U_{95\%}$ [g]	0,01267	0,0088	0,0091	0,0101	0,0115	0,01137	0,0131	0,0107	0,0100	0,0130
C_c [g]	1,80E-5	1,80E-5	1,80E-5	1,80E-5	1,80E-5	1,80E-5	1,80E-5	1,80E-5	1,80E-5	1,80E-5
MR [g]	99,9026 ± 0,01267	99,6673 ± 0,0088	99,6653 ± 0,0091	99,2300 ± 0,0101	99,5233 ± 0,0115	99,7680 ± 0,01137	99,0420 ± 0,0131	100,1873 ± 0,0107	99,2233 ± 0,0100	98,9959 ± 0,0130

3.2. Sensor Calibration

While FSRs can be used for dynamic measurement, only qualitative results are generally obtainable. The force accuracy ranges from approximately ± 5% to ± 25% depending on the consistency of the measurement and actuation system, the repeatability tolerance held in manufacturing, and the use of part calibration. Typically, the part-to-part repeatability tolerance held during manufacturing ranges from ± 15% to ± 25% of an established nominal resistance. The force resolution of FSR devices is better than ± 0.5% of full use force. In order to evaluate the uncertainty of the developed device, an experimental procedure was implemented. The FSR characteristics are displayed below.

Table 2. Force Sensing Resistor Characteristics.

Parameter	Value
Size range	10mm diameter
Device thickness	1.25mm
Force sensitivity	<100g
Pressure sensitivity range	<0,1kg/cm^2
Part-to-part force repeatability	±15% to ±25% of established nominal resistance
Single part force repeatability	±2% to ±5% of established nominal resistance
Force resolution	Better than 0,5% full scale
Break force	20g
Stand-off resistance	>10M ohms
Switch characteristic	Essentially zero travel
Device rise time	1-2ms (mechanical)
Lifetime	>10 million actuations
Temperature range	-30^{o}C to 70^{o}C
Maximum current	1mA/cm^2
Sensitivity to noise/vibration	Not significant affected

The FSRs are constituted basically by thin electric conducting material, set up together, forming two sets of isolated plates with its respective electric terminals, as is shown Figure 2. On Figure 2(a) is shown the general structure with the resistive film, the conductor's plates and the semiconductor film. On Figures 2 (b) and (c) is shown the partial structure with the semiconductor film and the conductor metallic plates.

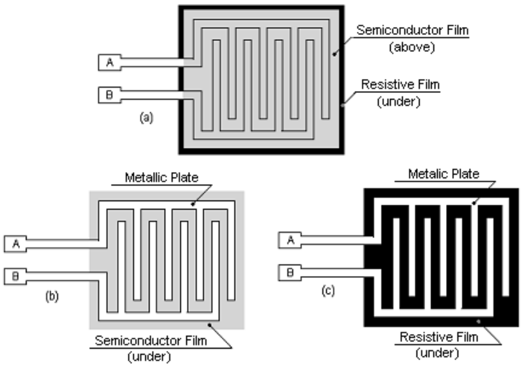

Figure 2. Layers of the FSR sensor.

One of the faces of this set of contacts is coated by a conductive polymer film, and the other face by a resistive film polymer material. In the normal conditions, that is, the sensor without mechanical effort, the conductance between the metallic plates is very low, of the order of 10-12S/cm^2. When a force is applied to the sensor, occurs a deformation of polymer of the resistive material that causes an increase of the faying surfaces between the two films improving the electric conductance between the plates.

In order to evaluate the characteristics of the FSR, a positioning device was confectioned to eliminate the errors coming from the uncorrected positioning of the mass pattern over the FSR. Following the orientation of the manufacturer, a FSR was fixed on a firm, plain and smooth surface (positioning device). We used an acrylic plate in our experiment. The active surface of the sensor was recovered with rubber supplied by the manufacturer to prevent the formation of air bubbles and contamination during its use. The ambient temperature of the metrological lab was controlled in 23^{o}C ± 0,5^{o}C during the performing of the tests. So, we isolate the system from errors coming from thermal variation. The instrument used in the measurements was Digital Multimeter HP 34401A with the following characteristics:

- Display: 6 ½ digits;
- Uncertainty: ± 0.150% reading +0.06% range for resistance readings;
- Uncertainty: ± 0,0045% reading + 0.0010% range for continuous voltage readings;
- Ranges: Voltage 0 to 10 Vcc; 0 to 100 kohm.

As can be seen at Figure 3, the resistance of the FSR sensor vary in the opposite direction to the applied force over the FSR sensor.

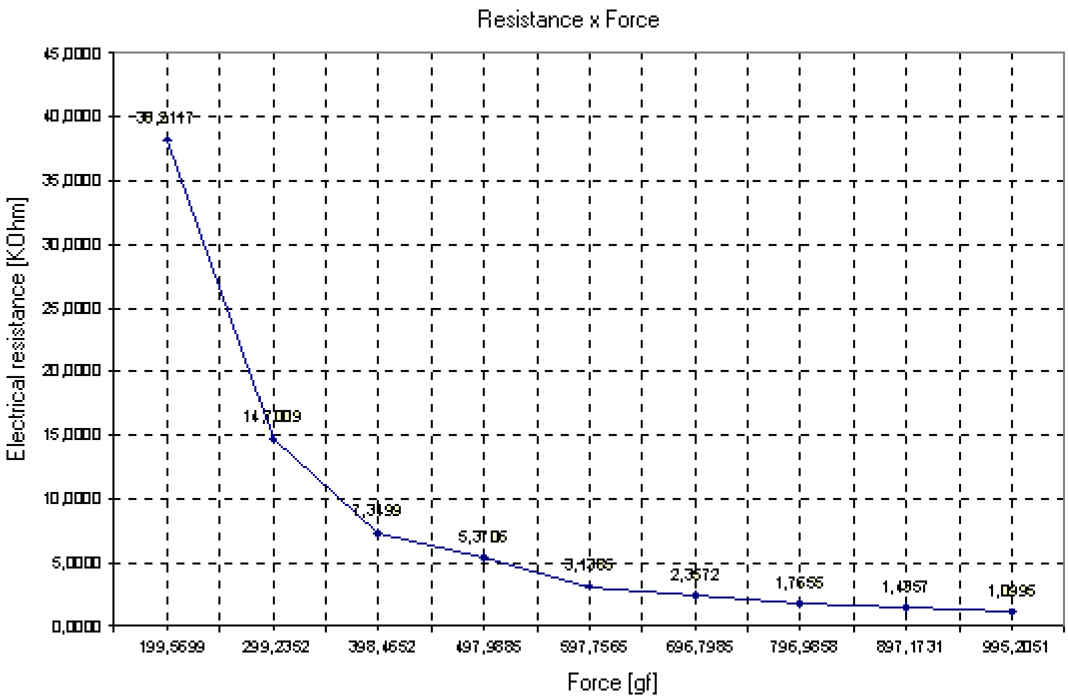

Figure3. Resistance variation of FSR sensor.

The sensor was insensible to forces below 100gf. On this graphical result, we can see three different regions. In the first, forces between 180gf and 300gf, the resistance decreases abruptly. In the next, forces above 300gf and below 900gf, the resistance decreases slowly with the force increasing. Above 900gf, the resistance saturates with the increasing of the force. The results presented on Figure 3 were already fixed using the expanded uncertainty. The maximum error on the range is 2,62% in relation to the average values of the resistance.

On the footswitch application, the goal is to measure if the foot hit or not the ground. So, the saturation value is not a problem. Below will be presented some graphical results during a real test (figures 5 and 6).

3.3. Electronics Calibration

Figure 4 shows the electronic diagram used in the implementation of the system for force measurement. As the force increases, the resistance of sensor FSR decreases. The input voltage on circuit (Vi) and output voltage (Vo) of the operational amplifier LM324 are acquired in order to evaluate the sensor response. The LM324 is used as signal conditioning or isolated buffer. The output voltage (Vo), varying up to 5 V, is applied in one of the analogical input of the microcontroller. The electronic circuit shown at Figure 4 takes the conversion of the resistance values to voltage levels and provides impedance isolation between input and output. Each sensor is connected to a circuit like that, so we have eight operational amplifiers connected to the analog inputs of the analog-to-digital converter of the microcontroller.

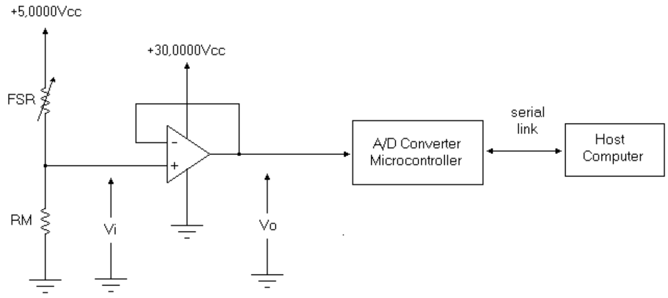

Figure 4. Electronic circuit for processing of force/pressure information.

To evaluate the force/voltage relation, a precision continuous voltage source (HP6114A) was used. This voltage source was applied to one FSR terminal and also the operational amplifier. The RM resistor was measured with HP 34401A in a constant temperature (25°C) and the value measured was 4,540±0,013kohms. RM resistor was determined to limit the sensor current, not to exceed 1 mA/cm^2, and to make the operational amplifier work on the linear region. The value of Vi and Vo were also measured in order to evaluate the operational amplifier gain. The gain of the operational amplifier (isolator) was checked and the found value was 1, with negligible error (less than 10^{-5}).

By using the ten masses and the presented system, the output voltage was read and in Figure 5 the result is presented. The values presented were already fixed because of the uncertainty influence. As described by the FSR manufacturer, the answer of the sensor is not linear.

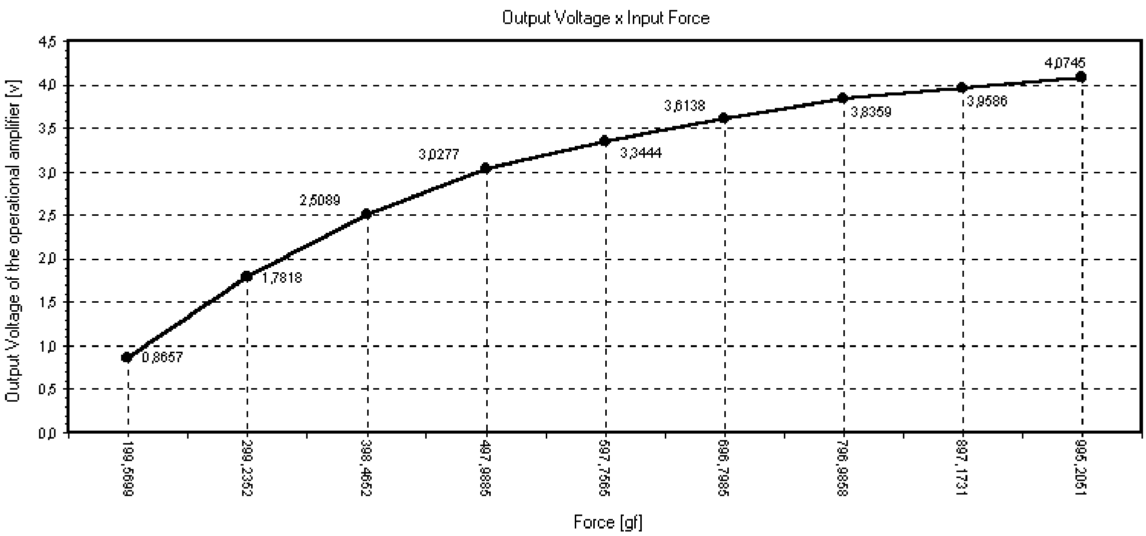

Figure 5. Output voltage of the signal conditioning circuit.

4. SOFTWARE INTERFACE

The software interface was developed to help the physiotherapist to identify and evaluate the pathology of the patient. The data acquired will be also used to check if the treatment is improving the patient's results. First of all, some patient data should be informed and saved in the data bank. Personal information such as: name, address, telephone numbers, weight, height and age are saved in a data file. The data acquired from the sensors are saved in a vector where the software knows which column data correspond to its respective sensor.

The human-machine interface was developed to be user friendly (Figure 6). Using Windows® resources, graphical facilities were developed, making possible the choice of graph each channel will be displayed on. In the physiotherapy studies, one treatment may demand temporal analysis of some particular signals (points at the patient's foot) and their correlation. In another different treatment, the interested signals and their correlation may differ from the previous ones. The developed software allows the user to select which signals will be displayed on the screen and then analyze their temporal correlation.

Some computational resources has been implemented to get time and amplitude measurements automatically. The user (the physiotherapist) can configure a reference line on x axis or y axis to the time and amplitude respectively. He can also use the cursor to get a particular point measurement, as shown at Figure 6. In the right upper corner of each graph a register presents the value of pressure and time corresponding to each point where the cursor is.

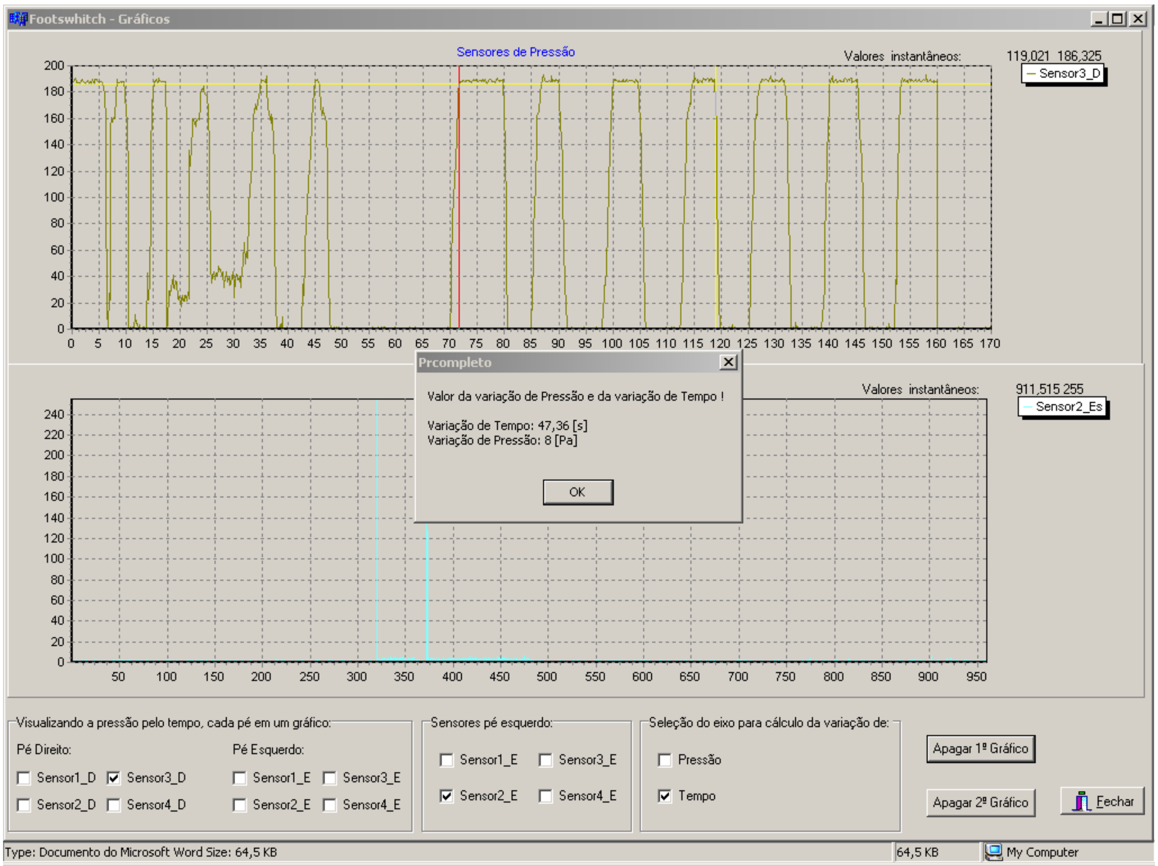

Figure 6. Measured data from the microcontrolled hardware.

5. CONCLUSIONS

One of the objectives of this project was the use of the FSR sensor to measure force/pressure in the feet of the patient. In the beginning, the force/pressure information would be used to indentify when a particular sensed foot point on the feet of the patient touched the ground, as well as the force/pressure intensity during the touch. It was observed that the time response of FSR sensor is short enough for this application, but the sensor is not suitable for precise force/pressure intensity measurements. The FSR response is very sensitive to the distribution of the applied force/pressure. A consistent weight (force/pressure) distribution is more difficult to achieve than merely obtaining a total applied weight. To get a better response it is necessary to keep constant the FSR actuation area, shape and compliance. Changes in these parameters alter significantly the response characteristics of the sensor. For the proposed application, these parameters change too much; so, a precise answer of the sensor cannot be reached. In other to get force/pressure information for a linear measurement, a new type of sensor should be found. For instance, time measurements during the patient walk can be precisely acquired. In order to evaluated the walk, verifying when each point of the foot touch the ground, the prototype developed here is more than appropriate. By using the proposed system the therapist can observe, save and measure time between selected events during the patient's walk for clinical evaluation of rehabilitation techniques for orthopedic pathologies. Using the footswitch system, the retest reliability of the temporal and distance parameters of gait was investigated within sessions for stroke patients in the early stage of rehabilitation.

6. ACKNOWLEDGEMENTS

This work was carried out at Grupo de Estudos em Automação e Robótica – GEAR – PUC Minas. The authors gratefully acknowledge the support of the PUC Minas (grant FIP2003/02P), the Mechatronic Engineering undergraduate student Ramon Guelber Martins who helped with graphic interface, and the Physiotherapy undergraduate students Rodrigo Queiroz Faria and Felipe Cândido de Oliveira, who work with the authors in the specification of the system, and finally to Prof. Alex Guazzi, who took the place of Prof. Renata N. Kirkwood on the supervision of this project at PUC Minas.

7. REFERENCES

Allard, P., Stokes, V.P., & Blanchi, J.-P., 1995. "Three-dimensional analysis of human movement". Windsor: Human Kinetics.

Amadio, A.C., Costa, P.H.L., Sacco, I.C.N., Serrão, J.C., Araujo, R.C., Mochizuki, L., & Duarte, M., 1999. "Introdução a análise do movimento humano - Descrição e aplicação dos métodos biomecânicos de medição". Revista Brasileira de Fisioterapia, Vol. 3, pp 41-54.

Birge, S.J., Morrow-Howell, N., & Proctor, E.K., 1994. "Hip fractures". Clinics in Geriatric Medicine, Vol. 10, pp 589-609.

Dieck, R.H., 1997. "Measurement Uncertaninty – Second Edition". An Independent learning module from the Instrument Society of America.

Embree, P.M., Kimble, B., 1991. "C Language algorithims for digital signal processing", Prentice Hall, Englewoods Cliffs, New Jersey, USA.

Gonçalves, A.A., 2002. "Metrologia". Laboratório de Metrologia e Automatização, Departamento de Engenharia Mecânica, Universidade Federal de Santa Catarina.

Grabiner, P.C., Biswas, T., & Grabiner, M.D., 2001. "Age-related changes in spatial and temporal gait variables". Archives of Physical Medicine and Rehabilitation, Vol. 82, pp 31-35.

Interlink Electronics data sheet, 1999. "Integration guide and evaluation parts catalog with selected interfaces". 546 Flynn Road, Camarillo CA 93012.

Jamsa, C., 1999. Aprendendo C++. Editora Makron Books. 1999. São Paulo-SP.

Kerrigan, D.C., Lee, L.W., Nieto, T.J., Markman, J.D., Collins, J.J., & Riley, P.O., 2000. "Kinetic alterations independent of walking speed in elderly fallers". Archives of Physical Medicine and Rehabilitation, Vol. 81, pp 730-735.

Mateus, C.A., 2000. C++ BUILDER 5 Guia Prático. Editora Érica Ltda. 2000. São Paulo-SP.

Microchip data sheet, 2001. "Micontroller PIC18F877 – user guide".

Õunpuu, S., 1995. "Clinical gait analysis". In B.S. Spivack (Ed.), Evaluation and Management of Gait Disorders. pp 1-51.

Tocci, R.J., Laskowski, L.P., 1983. "Microprocessadores e microcomputadores :hardware e software – Segunda Edição", Rio de Janeiro, Prentice-Hall.

Winter, D.A., 1991. "Kinetics". In University of Waterloo Press (Ed.), The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological. Waterloo: University of Waterloo Press. pp 35-49.

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