A Low Cost Wireless System to Monitor Plantar Pressure using Insole Sensor: Feasibility Approach

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Abstract: Plantar pressure analysis is an important strategy applied in clinical, orthopaedics, sports and rehabilitation studies. In this context, this work describes the development and application of wireless system to monitor plantar pressure. This system is composed by a data acquisition module based on low cost electronic instrumentation, high resolution insole flexible pressure sensor and Java application for data real-time visualization. To verify the feasibility and effectiveness of the system, workbench tests were realized and a healthy subject performed pilot trials based on static and dynamic activities on the biomechanics platform. According to the preliminary results, this system is effective to show the interaction between the foot and floor in static and dynamic conditions, presenting a measurement range of pressure of 0-300kPa and rapid response, among other features. Thus, this system is a feasible tool for quick and practical mapping of plantar pressure.

1 INTRODUCTION

Plantar pressure monitoring is an important tool applied in clinical, sports and rehabilitation studies. The systems that include this technology can identify pathologies, characterize gait cycles and evaluate standing posture (Hills et al., 2001; Girard et al., 2010; Bellizzi et al., 2011; Kaercher et al. 2011; Chapman et al., 2013; Ledoux et al., 2013; Robinson et al., 2013; Melvin et al., 2014).

Many researchers have developed self-constructed plantar pressure measurement systems (Castro and Cliquet, 2000; Smith et al., 2002; Saito et al., 2011; Crea et al., 2014; Motha, Kim and Kim, 2015; Tan et al., 2015). However, the development of these self-constructed devices requires time and a validation procedure. An alternative is the use of commercial pressure measurement systems.

Nowadays, some commercial systems stand out in the analysis of motion and gait. Freemed Baropodometric Platform (Sensor Medica SAS, Guidonia Montecelio, Rome, Italy) allows assessing balance, and detecting the foot loads and patient's posture during walking/running and standing.

The Medilogic Insole (T&T Medilogic Medizintechnik GmbH, Schönefeld, Brandenburg, Germany) uses flexible insoles with up to 200 resistive sensors to detect the plantar pressure distribution. This system is an acceptable tool for measuring ground reaction forces in work activities, except for kneeling positions (Koch et al., 2016).

The Pedar System (Novel GmbH, Munich, Bavaria, Germany) is a measuring system for monitoring pressure between the foot and footwear. Elastic insoles with up to 99 capacitive sensors that cover the entire plantar surface detect the pressure.

The F-Scan System (Tekscan, Inc., Boston, MA, USA) employs flexible tactile resistive sensor (up to 954 sensels) to obtain dynamic information about foot function and gait.

Flexible tactile sensor for measuring pressure distribution consists of two flexible substrates joined by adhesive and dielectric layers. Electrodes of both substrates establish a matrix of rows and columns, and each intersection forms a sensing element (SE) that changes its electrical resistance (R_s) when force is applied to it (Test & Measurement, 2014; Podoloff et al., 1991).

For flexible pressure sensor is recommended to follow the 100/70 Rule. Thus, 100% of the force should be concentrated within the sensing area of

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sensor, and 70-85% of the sensing area should be loaded. It is advisable to use a load actuator to distribute and to point the load (Flexiforce® Force Sensor Design & Integration Guide, 2015).

Price, Parker and Nester (2016) evaluated Medilogic, F-Scan and Pedar systems in relation to validity and repeatability. According to them, Pedar system presented greatest accuracy and repeatability when compared to Medilogic and F-Scan systems.

Using bench tests and subjects walking on a treadmill, McPoil, Cornwall and Yamada (1995) compared Emed (Novel GmbH, Munich, Bavaria, Germany) and F-Scan systems. High level of validity and reliability were reached by Emed whereas F-Scan was not satisfactory for certain measurements. Similar results were obtained by Hsiao, Guan and Weatherly (2002) through bench experiments.

This paper describes the development and application of wireless system to monitor plantar pressure. The system is composed by a data acquisition module based on low cost electronic instrumentation (less than US$20.00), high resolution flexible pressure sensor and Java application for data visualization. This system was designed for quick and practical mapping of plantar pressure, representing an auxiliary tool for orthopaedics and biomechanical studies. To verify the feasibility of the system, workbench tests were realized and a healthy subject performed pilot trials based on static and dynamic activities on biomechanics platform.

2 MATERIAL AND METHODS

The system is composed by insole pressure sensor, data acquisition module and Java application. The microcontroller associated with the switching circuit selects a SE, doing a scanning procedure, and performs analog to digital conversion of voltage from amplifier circuits (Figure 1).

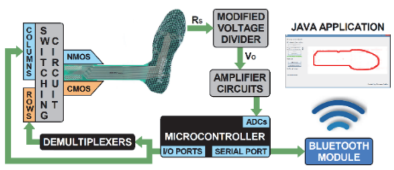

Figure 1: Block diagram of the system.

The switching circuit, including modified voltage dividers, convert R_s into voltage (V_O). Furthermore, the microcontroller provides serial data to Bluetooth module that sends it to Java application.

2.1 Insole Pressure Sensor and Apparatus for Characterization of Its Sensing Element

In this work, Medical Sensor 3000 (Tekscan, Inc., Boston, MA, USA) was used as insole pressure sensor. This sensor presents a foot-shaped area, and it can be trimmed to some sizes according to the reference lines. Top substrate has 60 electrodes that extend in widthwise in relation to the foot (rows). In lengthwise direction, bottom substrate presents two electrode sets - named as toes region (T) and heel region (H) - with 21 and 18 electrodes, respectively (columns). For convenience, columns were numbered from terminal side and rows were numbered from the border of two regions of bottom substrate, positive values for T and negative values for H (Figure 2).

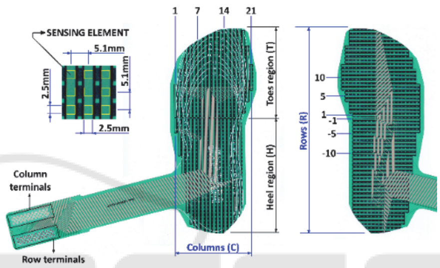

Figure 2: Bottom and top views of Medical Sensor 3000.

Columns and rows have width of 2.5mm and inter-electrode spacing of 5.1mm. The intersections between columns and row in sensor area create 954 SEs with area of 6.25mm^2. Force applied to opposite sides of the sensor changes the resistance of pressure-sensitive resistive material of each SE as a function of the force magnitude (Medical Sensor 3000; Podoloff et al., 1991).

Medical Sensor 3000 trimmed for U.S. footwear size 8 (26cm) were available for the developed system. Thus, this sensor presents 52 rows (1 – 23 and -1 – -29) and 29 columns (T3 – T18 and H4 – H16) monitored by electronic circuit.

According to the 100/70 Rule, a squared load actuator of 4.84mm^2 (PVC) was used to concentrate and to point the load within the SE. This load actuator was fixed on SE analyzed by double-sided tape (Figure 3a).

The structure showed in figure 3c was built in digital precision weight scale AS2000C (Marte Científica, São Paulo, SP, Brazil) to allow application of loads on the sensor, avoiding shear forces. For this, a polymer sleeve associated with a shaft of 50mm was fixed on its top (Figure 3b). The lower end of the shaft acts on the load actuator, while the upper end receives the support of loads. The applied loads resulting from the weight of: the support (7.3g), 10 blocks of 5g ($^{+0,7g}_{-0,4g}$), 15 blocks of 10g ($^{+0,4g}_{-1,0g}$), support plate of 21.4g and two blocks of 100g (±0.1g). Moreover, the load due to the weight of the shaft (12.8g) was also considered.

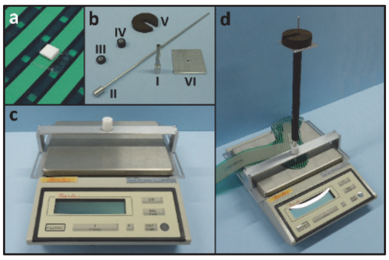

Figure 3: a) Load actuator fixed on SE; b) I - shaft, II - support of loads, III - 5g block, IV - 10g block, V - 100g block, VI - support plate; c) Custom built structure in weight scale; d) All loads applied to the SE; sensor fixed on weight scale plate.

Thus, 30 load levels were used for the characterization of SE (Figure 3d). The weight scale determined the exact value of each level during the application.

2.2 Data Acquisition Module

Data acquisition circuit was based on the modified voltage divider associated with the noninverting amplifier (Figure 4). As noted in the workbench tests (described hereafter) a linear relationship can be adopted between applied pressure and electrical conductance (C_s) of the SE, and the R_s varies between dozens of MΩ and 100kΩ for pressure range of 0 to 900kPa.

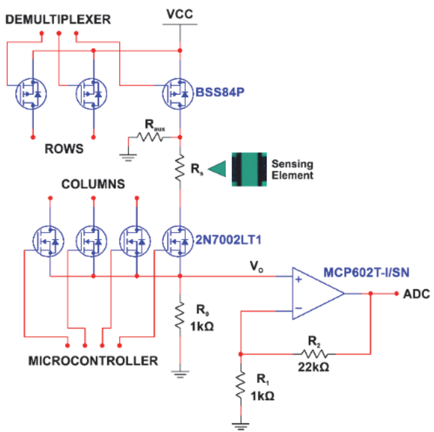

Figure 4: Schematic of data acquisition circuit, including switching circuit to select each SE. Whole circuit has eight sets with four NMOS and one operational amplifier.

About the modified voltage divider, V_O is given by equation 1. Since R_0 is much lower than R_s the equation 2 can be adopted. Thus, V_O is proportional to C_S, which establishes a linear relationship between applied pressure and V_O. The noninverting amplifier provides a gain of 10V/V.

$$V_O = \frac{R_0}{R_0+R_S} VCC \quad (1)$$

$$V_O = \frac{1}{R_S} R_0 VCC = C_S\, R_0 VCC \quad (2)$$

MOSFETs form the switching circuit. The electronic switching that selects the SE of insole pressure sensor is made by row and column. The rows and columns are energized when PMOS (null base voltage) and NMOS (positive base voltage) are turned on, respectively. Thus, R_S is selected when both switches are closed.

The microcontroller ATmega48 (Atmel Corporation, San Jose, California, USA) triggers both switches of each data acquisition circuit. It was used four ports (PD6, PB7, PD5 and PB6) to select the column, and each port was associated to an NMOS.

To determine the row, four ports (PB0, PB1, PB2 and PB3) act in four inputs of two demultiplexers, and two ports (PB4 and PD7) enable one of these demultiplexers. Each one of 32 outputs of demultiplexers was associated to one PMOS.

Finally, the operational amplifiers provides an amplified signal for each 10-bit analog to digital converter (ADC0 to ADC7) of the microcontroller.

In addition to selecting row and column, when the microcontroller is powered on, three functions are initialized: ADCs, I/O ports (configured as outputs) and serial port.

In relation to the serial port, the following configurations were set: double transmission speed, data transmission enabled, no parity, asynchronous communication, one stop bit and word of 8 bits. Moreover, according to the maximum baud rate of Bluetooth module (115.2kbps), the baud rate was set to 111.1kbps (clock of 8MHz).

The Bluetooth module HC-06 (Guangzhou HC Information Technology Co., Ltd., Guangzhou, Guangdong, China) transmits data from the microcontroller to other devices. This module receives a serial word in its RX port and sends it to paired devices. The transmission protocol is based on a start byte (255) followed by a data vector, it being made the synchronization between the transmitter and receiver for each start byte.

Entire electronic circuit was mounted on two double-face printed circuit boards, which also work as custom-built connector for insole pressure sensor.

Two demultiplexers, 32 PMOS and SMD resistors were mounted in the top board. Bottom board received the microcontroller, 32 NMOS, four operational amplifiers and Bluetooth module. Data acquisition module is powered by one 9V battery.

2.3 Java Application

The software written in Java Programming Language creates an image corresponding to the applied pressure in sensor. The *BlueCove* Application Programming Interface (API) used allows receiving data from the data acquisition module. This API is a Java library for Bluetooth.

This software consists of two main classes. The *PalmilhaThird* class contains the main method, which runs when the software is started. It creates a visible window that displays the program's graphic user interface (GUI) by invoking the constructor of the second main class, *JFrame*. *JFrame* specifies all the methods and components that will be available in the program's GUI. It also has two inner classes: *Bluetooth*, which handles Bluetooth communication, and *MainPanel*, which creates an image representing the SEs inside the GUI.

JFrame's constructor invokes the *initComponents* method, which initializes all the components of the GUI and configures its layout. Among the GUI's components, there are buttons that invoke methods. In the image, which is also a component of the GUI and is created by the *MainPanel* inner class, each *pixel* represents one SE, and its value and color are associated with the acquired pressure data, ranging from white (null pressure) to full intensity red (maximum pressure). *MainPanel* calculates the difference between the SE output value and the associated reference value. The bigger the difference, the more intense the red color of the *pixel* will be. Using RGB triplet, the colors belong to red scale from (255,255,255) to (255,5,5), that is, green and blue intensity values are associated and vary according to the pressure.

This application reads data provided from the Bluetooth connection and refreshes the images (25Hz) simultaneously, because it is composed in threads. Control of the image's *pixels* is performed in the *tmain* thread, which is created by the *JFrame*'s constructor and runs parallel to the *bt* thread. This thread is created using the *Bluetooth* inner class after a connection to a Bluetooth device was established.

Bluetooth has methods that perform the search for, establish and close a connection to Bluetooth devices (through default password 1234 for Bluetooth module HC-06), and read the SEs output values. The latter method saves the output values in a vector, for future comparison with the reference values, and implements a protocol to accelerate reception of repeated bytes, as it was observed that the "zero" byte is received frequently. In this protocol, if a byte is repeated more than four times, it's transmitted as a sequence of 4 bytes. The first byte holds the flag value (254), the second holds the value of the repeated byte, and the third and fourth byte hold the MSB and LSB of the number of times the value was repeated.

2.4 Workbench Tests for Sensor Characterization and Verification of System Performance

First stage of workbench tests was based on applying 30 load levels within one SE of sensor. For each load values the R_s was measured by means of a digital multimeter 17B+ (Fluke Corporation, Everett, WA, USA), allowing to observe the relationship between pressure and R_s. This activity was repeated five times, and mean and standard deviation (SD) were calculated for the R_s and pressure. The relationship between the C_s and the pressure was also established.

According to the position numbering (row, column) described previously, analyzed SE was (-26,11H) – region of heel.

This same procedure was performed for complete system, that is, insole pressure sensor connected to the data acquisition module and the software that displays data acquired by means of wireless connection. Thus, the pressure employed was associated to the color intensity of graphic element that represents the SE.

The Biomechanics Platform OR6-7-1000 (AMTI Advanced Mechanical Technology, Inc., Watertown, MA, USA) was used to verify the system performance (Figure 5). This equipment presents a sample rate equals to 240samples/s and all data are processed by low pass filter (10.5Hz).

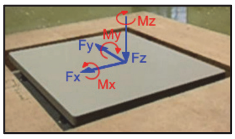

Figure 5: Biomechanics Platform – sign convention for the force and moment components defined by AMTI.

A healthy subject fixed the data acquisition module on his right leg by Velcro strap and placed the insole sensor pressure in the right footwear. Firstly, the load due to subject's body mass was measured.

The verification of system performance was based on two activities (static and dynamic). During static activity, the subject transferred his load from the left lower limb to the right, and returned to the initial position; nine load levels (Fz) were considered. Figure 6 shows 7 positions of the subject related to this activity.

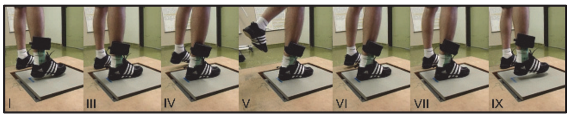

Figure 6: Subject performing static activity.

The dynamic activity was based on a step on the platform (Figure 7). The moment applied on the Y-axis (My) was considered to verify the transfer of the load from the heel to the toes of the right foot.

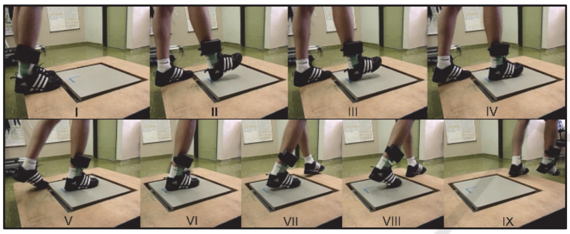

Figure 7. Subject during dynamic activity.

3 RESULTS

Using 100/70 Rule, the SE presented a very high R_s to zero pressure, allowing it to be considered as an open circuit. Thus, the C_s becomes zero. Figure 8 shows the relationship between applied pressure and R_s and C_s.

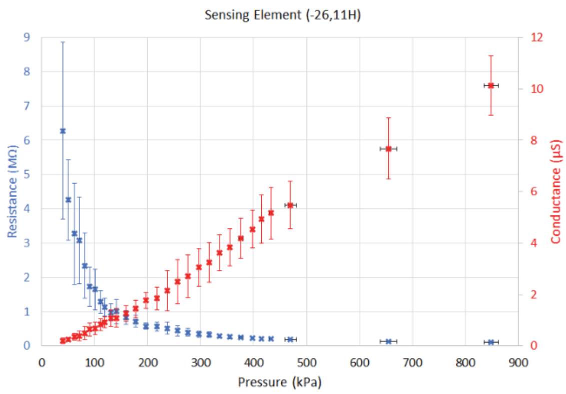

Figure 8: Characterization of SE in relation to applied pressure and R_s and C_s.

For a better visualization of the other points, the first point associated with the pressure 25.7(0.4)kPa was not included in the graph. The respective values of R_s and C_s were 24.7(14.4)MΩ and 0.06(0.05)µS.

Figure 9 shows the wearable device composed by the data acquisition module with Medical Sensor 3000 embedded in it. The data acquisition module, which has small dimensions (120x80x33mm) and low weight (160g and 205g with battery), is fixed to the user's leg by a strap and the sensor is inserted into the footwear during the plantar pressure mapping. This device consumes up to 42mA and it may be used bilaterally.

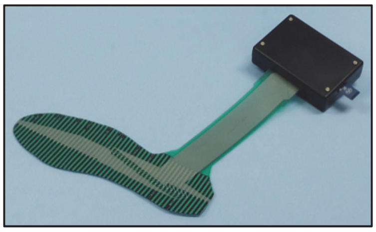

Figure 9: Wearable device: data acquisition module and Medical Sensor 3000 (215g).

Bluetooth module HC-06 kept the connection up 20m even with two wooden walls between the transmitter and receiver, without data loss.

In addition to the area intended for the insole pressure sensor representation, the front panel of Java application presents buttons related to the Bluetooth connection and displayed data (Figure 10).

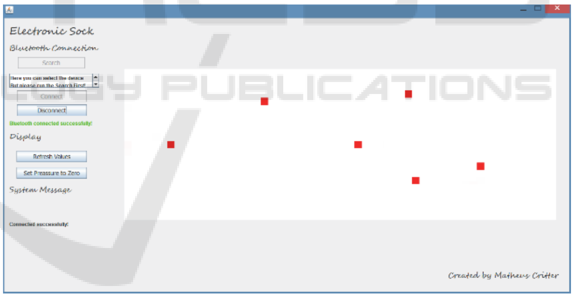

Figure 10: Front panel of Java application showing five saturated SEs (left foot): (-26,11H), (-13,5H), (1,11T), (8,4T), (9,16T) and (18,14T).

"Search" button allows finding paired devices. Device services are selected through the password, and they are listed in the scroll box. The HC-06 service must be selected and the connection is established through the "Connect" button. Thus, status message "Bluetooth not connected…" becomes "Bluetooth connected successfully!".

"Set Pressure to Zero" button allows the user to calibrate the system, setting the reference values, and the "Refresh Values" button to refresh the *pixel* values in the image. The "Disconnect" button disconnects the system from the Bluetooth device.

For complete system, the sensor saturated at

296.4(1.9)kPa, that is, the color intensity of graphic element became bright red (255,5,5) from this value during the five measures. In figure 11, the marker represents the graphic element generated by Java application. Its color was obtained from the mean (approximated to integer) of the green and blue intensity values.

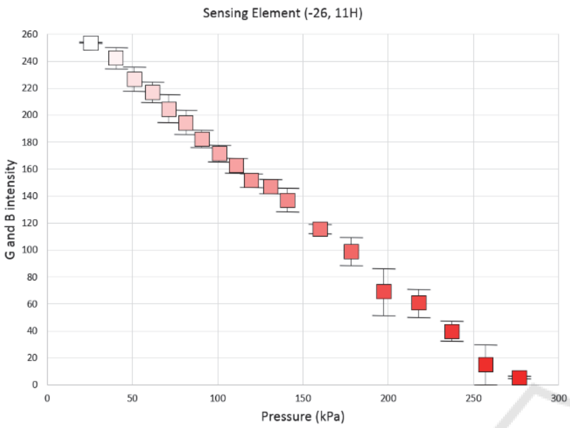

Figure 11: Color of graphic element according to the employed pressure. Mean and SD were approximated to integer values.

Synchronized data from the Biomechanics Platform and the wearable device allowed relating the plantar pressure with the force and the moment for static and dynamic activities, respectively. Also synchronized, the camcorder captured the activity images. For better visualization, all images of right foot plantar pressure were mirrored.

As a reference value, the load due to subject's body mass resulted in 735.2N applied on Z-axis (Fz) of Biomechanics Platform. This value was achieved during static activity, as shown in figure 12 (points IV and V).

Point I indicates initial contact of right foot with the platform. The points II and III show the progressive loading up to the full contact, indicated by the baseline (points IV and V). In contrast, points VI, VII and VIII characterize the process of unloading up to no contact between the foot and the platform (point IX).

For the step on the platform, the plantar pressure was associated with applied moment on Y-axis (My). According to the figure 13, the heel strike occurred in point II; from there, the pressure applied by heel increased up to the maximum value (point IV). After this, the pressure began to be distributed, achieving the foot flat phase (point V).

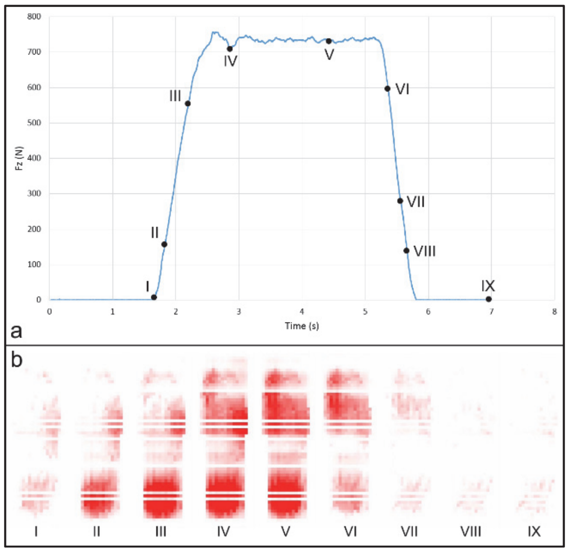

Figure 12: Load transfer from the left lower limb to the right: a) Force measured by Biomechanics Platform; b) Plantar pressure detected by the wearable device.

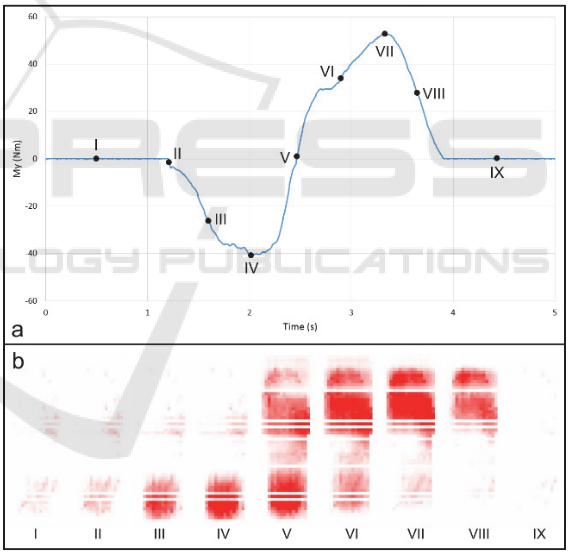

Figure 13: Load transfer from the heel to the toes: a) Moment measured by Biomechanics Platform; b) Plantar pressure detected by the wearable device.

Following this phase, the pressure exerted by the heel decreased, while the pressure of the toes and metatarsal region increased, characterizing the transfer of the load (points VI and VII). The point VIII showed the foot on heel off phase – on the verge of toe off phase.

Points I and IX demonstrated the plantar pressure for the foot at the limit of no contact and in swinging, respectively.

4 DISCUSSION

The apparatus built for characterization of the SE allowed application of loads with high repeatability up to about 480kPa, as showed in figure 8. Thus, it can be considered an effective tool for this pressure range because the SE practically reached the saturation at this value, although the manufacturer informs that the pressure capacity is 850kPa (Medical Sensor 3000).

Considering the mean values, the relationship between R_s and pressure is a power function with a negative exponent. Moreover, a linear fitting is suitable to the relationship between C_s and pressure, facts that are in agreement with the manufacturer and other studies about flexible pressure sensors (Yaniger, 1991; Kalamdani, Messom and Siegel, 2006; Flexiforce® Force Sensor Design & Integration Guide, 2015).

The analysis of the SE showed that for low pressures, the repeatability of R_s is poor. According to the manufacturer, this behavior can be attributed to the use of a standard multimeter, since most do not provide a constant voltage. Woodburn and Helliwell (1996) also reported poor repeatability of the sensor. This feature has become better from 150kPa.

However, the data acquisition module uses the C_s, which presents opposite behavior in relation to R_s, to determine the output of electronic circuit. Thus, repeatability and linearity can be attributed to the complete system, being confirmed by the results obtained in workbench tests (Figure 11).

In relation to modified voltage divider, the transistors used presents low electrical resistance (up to about 8Ω), when they operate like closed switch. This value is much lower than R_s, not interfering in the performance of the circuit. R_{aux} was employed to ensure rapid discharge of transistor drain voltage, avoiding interference between adjoining SEs.

The design and development of the entire graphic platform for visualization and data acquisition also follows the porting concept. Therefore, the software for interface and Bluetooth connection was implemented in Java Programming Language, which is able to execute the same procedure on different operating systems (e.g. Windows, Linux). This feature occurs because Java applications run in a virtual machine.

The library *swing* allowed the implementation of the GUI to display the insole pressure area and to control the Bluetooth connection. Although *swing* is one of the most extensive libraries, its classes and methods also guarantee compatibility among computers with different screen resolutions, keeping the high level of porting both for the execution and for the visualization of the experiments.

It is important to mention that unlike *swing*, the *BlueCove* is not inherent in the Java development platform. This library is originally an Intel research project for Bluetooth communication and it is currently maintained as an open-source project. In addition, the computer, which runs the application, must have Bluetooth capabilities, such as the hardware and driver installed correctly.

About verification of performance through activities realized by subject, the system was effective to characterize the foot pressure applied during both conditions.

For static activity, the system presented rapid response, identifying a variation of about 700N in 1s, with intermediate values also characterized (Figure 12, points I, II, III and IV). In addition, the system represented the load transfer from the left lower limb to the right in an appropriate manner. At the moment that the load was fully applied to the right limb, the system indicated a higher pressure in the region of the fifth metatarsal (Figures 6 and 12, point IV). When the position of the subject was stabilized, the pressure was distributed throughout the metatarsal region and the hallux (Figures 6 and 12, point V).

The dynamic activity can be considered a partial gait cycle, and some phases are identified through pressure distribution pattern. Considering the right lower limb, the subject performed the stance phase of the gait cycle. According to the figures 7 and 13, point II marks the initial contact (heel strike) and loading response phase includes point V (foot flat). Midstance is related to point VI, being followed by the terminal stance. In this phase occurs heel off (point VIII), and the stance phase is finished with preswing (toe off).

Finally, the range of pressure measured by the system is suitable for many applications, e.g., the mean value of plantar pressure during walking is 140kPa (Keijsers, 2013).

5 CONCLUSIONS

In this paper, the development and application of a system to monitor plantar pressure based on a wearable device were described. According to the preliminary results, this system is effective to show the interaction between the foot and floor in static and dynamic conditions, like standing and walking, respectively. Thus, this system is a feasible auxiliary tool for clinical, orthopaedics and rehabilitation analysis. Low cost, high resolution insole flexible pressure sensor, easy wearability, no discomfort, wireless data transfer, software porting and real-time visualization of pressure mapping are outstanding features of this device in relation to other self-constructed and commercial systems. However, the sensor is sensitive to temperature and it is necessary to disassemble the data acquisition module to change the sensor, e.g., to use a sensor with other size.

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