A Mechatronic System Mounted on Insole for Analyzing Human Gait

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***Abstract*—In this paper, designing and fabricating a mechatronic system for analyzing exerted forces by human gait has been described. Force sensitive resistors (FSRs) sensors as well as Arduino Due (Microcontroller) have been utilized in the system which is mounted on a shoe insole. Furthermore, the applied Interrupt Service Routine (ISR) programming technique in microcontroller and signal conditioning circuit design has been explained. The mechatronic system has been tuned and calibrated through the experimental tests and some of the important results have been presented and discussed.**

***Keywords*— Force sensitive resistors (FSRs), Arduino Due, insole, force platform, gait**

I. INTRODUCTION

It might be indeed true to say that human body motion has been under investigation since about fifty years ago. Several researchers focused on analyzing human body motion from different points of view; in fact, there are some motivating reasons for them. From scientific perspective, realizing and comprehending details of human motion is an important problem. Walking and running efficiently; that is, moving with minimum energy consumption is an interesting issue for the sportive researchers. From the medical point of view, diagnosing and preventing some injuries and diseases such as diabetes can be done by analyzing body motion. Ankle moment has a remarkable effect on trunk acceleration propulsion, and balance while walking [1].

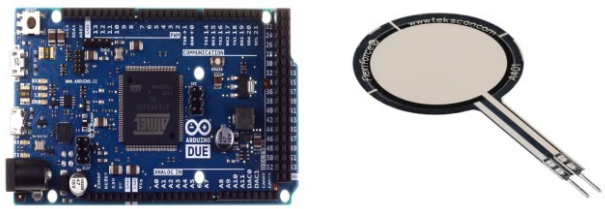
Some types of systems are using air coils in the shoes for measuring the pressure in order to monitor human gait, as in the work by Kyoungchul in [4]. Furthermore, different kind of instruments have been presented so far for gait event detections or fault diagnostician [5]–[9]. Generally speaking, recognition and analysis of the human gait can be subdivided in three different approaches: image processing, floor sensors and sensors placed on the body [10].

Precise result from motion Kinect requires analyzing the steps during walking on a surface of the force plates; otherwise, may lead to inaccuracies. Many methods have been developed in order to analyze human walking. Infrared cameras and force plates have been used in some laboratories because of their accurate measurement and also availability of standards for them. The high price is the main disadvantage of these type of instruments. Some other types of instruments such as treadmills are available but walking in a normal way is different from walking on the treadmills. Moreover other types of instruments are commercially available in market but they are expensive products so they are not easily available for general usage [2], [3].

A simple cheap footswitch system has been presented in [11] in order to measure accurately the initial and end foot contact time. The idea of this footswitch not only has been widely used in the systems for mobile gait analysis, but also is used in our work for the purpose of building an accurate and inexpensive mechatronic system mounted on a shoe insole with use of force sensitive resistors (FSRs). Applying FSRs sensors result in high nonlinear-response which leads to difficulty in parameters calculating that is a challenging problem for designing a measurement system for gait analysis [12].

In this paper, the design and the test of a mechatronic system mounted on insole platform in order to measure and analyze force reaction during walking is discussed and presented. The mechatronic system is based on two main parts: the sensorial insole and the data acquisition device. The shoe insole includes five force sensitive resistors (FSRs) with separated signal channels. The main part of data acquisition block is a microcontroller (Arduino) for ADC conversion and data logging on a SD card. For calibrating the system and finding the most optimized coefficient of conversions (volt-newton) and also reducing the value of RMS of error signals, a force platform has been used.

Although a number of works and products has been done in this area and some of them are similar to our work such as newest one in [13], there are some remarkable difference



(a) (b)

Fig. 1. a) Front view of Arduino Due, b) FSR sensor (Flexiforce A401)

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between our work and the others. Using low-cost instruments, average error of 5% and the minimum invasiveness at the end of the athletic gesture are the main advantages and differences between our work and the others.

This paper is organized as follows: Section II briefly explains the data acquisition technique. The description of the sensors is give in Section III. Section IV provides a description on the system realization. In Section V the methodology of calibration and tuning has been discussed.

II. DATA ACQUISTION

Data acquisition and logging is performed by a custom microcontroller system that has the ability of recording the measured data on a SD memory card. In our system the Arduino Due (Fig. 1.a) which is a microcontroller board based on the Atmel SAM3X8E ARM Cortex-M3 CPU [14] has been used for force data logging on a SD card. In our system the Arduino Due (Fig. 1.a) which is a microcontroller board based on the Atmel SAM3X8E ARM Cortex-M3 CPU [14] has been used for force data logging on a SD card.

First, the available data values will be copied in the first cell of the circular buffer, then they will be transferred from the buffer to the memory card. The last step will be done during the pause time between two sequence acquisition times. Fig. 2 illustrates the flowchart of the main program of microcontroller (Arduino Due). The Fig. 2.a shows the main program flowchart for data acquisition of the received signals and saving data on a memory card. The flowchart of the program for Interrupt Service Routine (ISR) of data sampling is illustrated in Fig. 2.b.

According to Fig. 2, once the sampling ISR has been completed, the microcontroller goes back to the main () loop, in which the acquired samples are transferred to the SD card. When the timer generates another interrupts (so the sampling Routine is started again), the transfer is stopped and can be restricted once the ISR is completed.

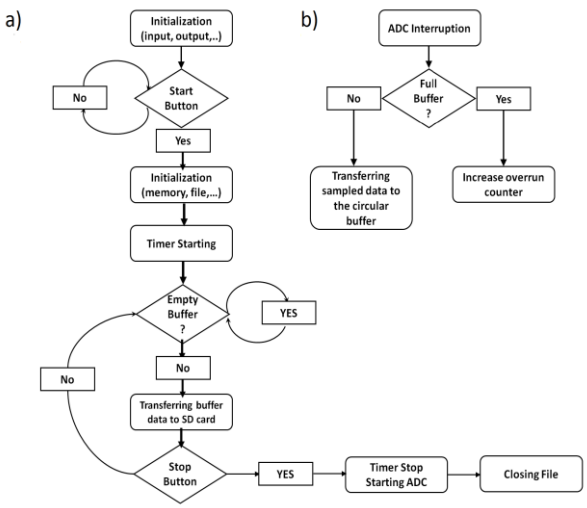


Fig. 2. Flowchart of Arduino program, a) the flowchart of the main () program, b) the flowchart of the interruption service routine (ISR) program for data sampling

TABLE I
TYPICAL PERFORMANNCE OF SENSOR FLEXIFORCE A401

Typical Performance	Evaluation Condition
Linearity (Error) < ± 3%	Line drawn from 0 to 50% load
Repeatability < +2.5% of full scale	Conditioned sensor, 80% of full force applied
Hysteresis < 4.5% of full scale	Conditioned sensor, 80% of full force applied
Drift < 5% per logarithmic time scale	Constant load of 25 lb (111N)
Response Time < 5 µsec	Impact load, output recorded on oscilloscope

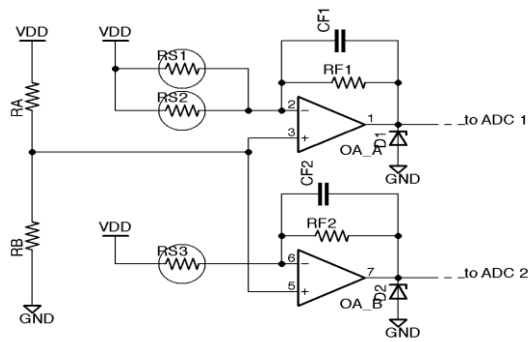
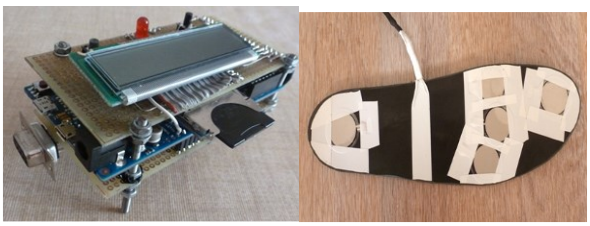


Fig. 3. Signal Conditioning Circuit (In the figure, only two channels of six channels have been demonstrated)



(a) (b)

Fig. 4. a) The mounted boards of the acquisition system. In order from the bottom: Signal conditioning circuit (on the left side, the arrived signals connector from the sensors is visible), the board of Arduino Due, the control board with the SD slot for memory and the display, b) Sensorial insole, the five Flexiforce A401 sensors are visible

III. SENSORS

A. FSR Sensors

The measurement of the ground reaction force (GRF) is done by force sensing resistors (FSR). This kind of the sensors are frequently used in similar works [13], [15], [16]. Teksan Flexiforce A401 (Fig.1.b) is the type of the sensor that has been chosen in our system. The typical performance of this sensor is reported in Table I.

B. Signal Conditioning Circuit

Signal conditioning circuit which is a conductance-voltage convertor, has been used to convert the received signals from

sensors in readable mode for ADC (Analog Digital Converter). Fig. 3 shows the signal conditioning circuit; R_{S1}, R_{S2} and R_{S3} are the resistive sensors. The DC gain of the first channel can be calculated by considering the superposition effect as follows:

$$V_{out2} = -V_{DD}\frac{R_F}{R_{S1}} - V_{DD}\frac{R_F}{R_{S2}} + V + \left(1 + \frac{R_F}{R_{S1}||R_{S2}}\right) \quad (1)$$

By reorganizing the equation 1, the following equation can be obtained:

$$V_{out2} = -\Delta V\frac{R_F}{R_{S1}} - \Delta V\frac{R_F}{R_{S2}} + V_+ \quad (2)$$

Where $\Delta V = V_{DD} - V_+$ and $V_+ = 3.2\,Volt$ for Arduino Due.

As it can be seen in Fig. 3, two 3.6 Volt Zener diodes (D_1 and D_2) are mounted in parallel to the output. These diodes act as a voltage protection for the inputs of the ADC channels. In fact if the voltage of one of the input pins surpass the breakdown voltage of the Zener diode, the diode acts and prevents the probable damages on microcontroller.

The values of R_A and R_B resistors are chosen 1.8 kΩ and 3.3 kΩ respectively. The value of the feedback resistor has been chosen to fully exploit the ADC range. Knowing that during running the reaction of vertical forces to the ground reaches up to twice the body weight [17] and estimating the maximum weight of a person on the test is 100 kg so the scale measuring system is based on 200 kg (less than 2000 N). Regarding the information on the data sheet of the Teksan Flexiforce A401 sensor, it is possible to estimate about the conductance of the sensor under 200 kg (440 lb) pressure.

The conductance / weight ratio can be calculates as:

$$m = \frac{G_S(120lb) - G_S(20lb)}{120lb - 20lb} = 1.6 \times 10^{-7}\left[\frac{S}{lb}\right] \quad (3)$$

With knowing the value of slope of the conductance/weight, the conductance can be evaluated as:

$$G_S(440lb) = m.f = m.440\ lb = 70.4\ \mu S \quad (4)$$

And the resistance of the sensor can be obtained as:

$$R_S(440lb) = \frac{1}{G_S(440lb)} = 14.2\ k\Omega \quad (5)$$

Now by considering the equation 2, the value of R_F (neglecting the second sensor) is:

$$R_{F2} = \frac{V_+ - V_{out}}{\Delta V}R_S = \frac{3.2V - 0.2V}{1.8V} \times 14.2\ k\Omega = 23.5\ k\Omega \quad (6)$$

The nearest commercial resistor to $RF_{\_DUE}$ is $22k\Omega$. The capacitor is also used in signal conditioning circuit in order to have a cutoff filter for the frequency about F_C=250 Hz and can be obtained as follows:

$$C_{F\_DUE} = \frac{1}{2\pi F_C R_{F\_DUE}} = 29nF \quad (7)$$

The nearest commercial capacitor to C_{F2} is 27nF. A filter capacitor has been used to reduce filter noise at high frequencies.

IV. System Realization

The final version of our system includes two main blocks: Data Acquisition Block and Sensorial Insole. The data acquisition block is mounted on a mounting box that is kept trough a belt on the person's body during the running; while, the sensorial insole is located in the shoe. The two blocks are connected with heavy duty multipolar cables.

A. Data Acquisition Block

The data acquisition block is based on three boards: The Arduino Due microcontroller board, an expansion board that mounts the slot for the memory card and some circuits for the control of the acquisition and the signal conditioning circuit for six separated channels of data acquisition.

These boards are positioned one above another and interconnected with the connector (header) so they can easily be disassembled for any changes or tune-ups. The final structure of data acquisition block is shown in Fig. 4.a.

B. Sensorial Insole

Fig. 4.b illustrates the last version of the sensorial insole that was placed in a shoe. As it can be seen, the sensors are located on a nominally flat surface. Several arrangements of force sensors have been investigated to experimentally determine the optimal placement, as shown in Fig. 5. The main advantages of this type of sensor location is that sensors can work in an optimal condition. The wiring was done with the normal copper wires at the bottom of the slab, cables and connectors are protected by sheaths shrink and held in place by adhesive tape.

V. Tuning and Calibration

Similar to other measuring systems also our system needs to be calibrated. In fact, our mechatronic system records and registers the behavior of the output voltage of the op-amp.

The gain of the signal conditioning circuit depends on the resistance of the circuit and can change the coefficient of the conversion.

By neglecting the fixed-terms, following equation turns up:

$$V_{out} = -\Delta V R_F G_S \quad (8)$$

Where the value of the conductance G_S is chosen approximately from the sensor data sheet. Regarding the presented material in section III:

$$G_S = m.F_{lb} \quad (9)$$

Where F_{lb} is the applied force on the sensor measured in pound. By substation the equation 9 in 8 and rearranging the expression for explication the fore, we can obtain:

$$F_{lb} = -\frac{V_{out}}{m\Delta V R_F} \quad (10)$$

For converting the force in pound to newton, multiplication to 4.45 is needed:

$$F_N = -\frac{V_{out}}{m\Delta V R_F} \times 4.45 \quad (11)$$

The value of ΔV is 1.8 V for signal the conditioning circuit of Arduino Due. Therefore, a conversion constant can be obtained:

$$k_{v\to N} = -\frac{1}{m\Delta v R_F} \times 4.45 = 702\left[\frac{N}{V}\right] \quad (12)$$

Noting that multiplication of this value by assuming the output swing of the op-amp causes in $702 \times 3 = 2180[N]$ which is the maximum force that the system measures.

In fact the reading carried out from the acquisition is not measuring of voltage but is direct reading of the digital conversion of the signal. Consequently, a range number from 0 to 4095 will present the voltage between 0 and full scale

voltage of ADC ($V_{FS\_ADC} = 3.3\,Volt$). Thus, it is possible to find directly the conversion between the numerical value converted by the ADC and the force:

$$k_{ADC\to N} = -\frac{1}{m\Delta V R_F} \times 4.45 \times \frac{V_{FS_{ADC}}}{2^N} = 5.66 \times 10^{-3} \left[\frac{N}{LSB}\right] \qquad (13)$$

A. Characteristic Limitation of the System

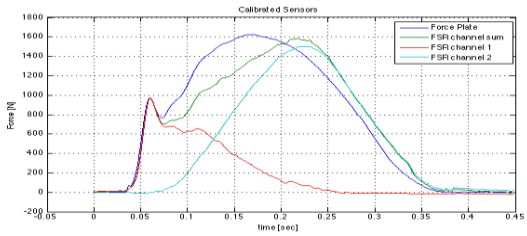


Fig. 6. Initial calibration of the sensors for comparison with the force platform

The technical limitations imposed by the choice of sensors and the variability of each individual body structure require the use of a proper calibration procedure. Also the insole mounted on the shoe can be in different forms that results in different force distributions during the walking. Moreover, the quality of the sensors, their positions and also conditions of their performance (humidity and temperature) can affect the performance of the system.

B. Calibration Methodology

We started from a configuration with 3 sensors on 2 separated channels and then a configuration with 5 sensors on 5 separated channels, as it can be seen in Fig. 5. The methodology used is based on linear regression, the method has been used in similar works where it seems to give good results, leading to an error close to 5% [13]. We can choose among two different strategies for calibration: 1) minimizing the RMS value of the error signal between the readings of the force platform and those of the sensors: this leads to have a behavior of the force which should approximate the overall performance of the platform with some margin of errors. 2) Minimizing the RMS error on the features: this should lead to a trace of the force that deviates the most from the force platform, but it will be less uncertainty about the value of the extracted features.

C. First Configuration

The first sensor configuration of the insole with three sensors and two separated channels is shown in Fig. 5.a. The position of the sensors are chosen in order to consider maximum pressure during the motion [18] . Some tests have been done in the laboratory with the force platform, in Fig. 6 the behavior of the acquired signals of sensors and the force platform has been used. The coefficient for the calibration have been found in a different way for the two channels. For the first channel (where the sensor is located under the heel) a multiplicative constant (K_1) has been found in order to match the amplitude of the first peak recorded by the sensors and the amplitude recorded from the platform. For the second channel the term (K_2) is to minimize the RMS value of the error signal given by:

$$e = f_{ForcePlate} - k_1 . s_{channel\_1} - k_2 . s_{channel\_2} \qquad (14)$$

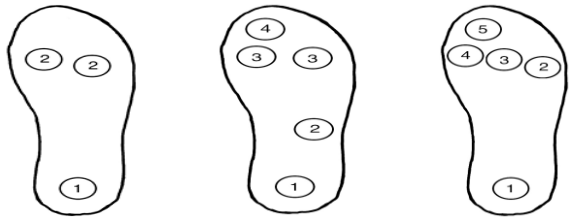


Fig. 5. Arrangement of the sensors on the insole in the a) first version

In which e is the error signal between the acquisition of the force platform and the sensors, $f_{ForcePlate}$ is the signal acquired from the force platform of strength and used as a reference, $K_{1.schannel}$ represents the first channel signal acquisition (k_1 is found by comparison of peaks), k_2 is the factor that multiplies the signal of the second channel and $s_{\text{channel\_2}}$ minimizes the RMS value of e.

Accurate force estimation, correct recording contact time and superimposed of initial part of curves could be concluded from Fig. 6.

D. Second Configuration

The aim of the second configuration is to achieve the greater accuracy of the curve and to obtain this goal, two additional sensors are mounted (four channels and five sensors in total). This arrangement of the sensors is shown in Fig. 5.b. The additional central sensor has the purpose of providing the missing information in the central phase of the step while the sensor located on the tip is used to obtain the information on the toe force.

TABLE I II

CALIBRATION COEFFICIENT K WHICH IS CALCULATED WITH USE OF MATLAB. THE VALUES OF EVERY ROW REPRESENTS THE MULTIPLICATIVE COEFFICIENT FOR ACQUIRED DATA BY THE SENSORS AND THEY ARE EXPRESSED IN $\left[\frac{N}{LSB}\right]$

CHANNEL	TEST 1	TEST 2	TEST 3	TEST 4
1	3.37	1.65	2.66	4.49
2	4.45	3.13	6.42	2.90
3	0.79	0	0	0
4	0	1.25	1.22	0.86
5	5.40	0.84	0	3.34

TABLE I III

RMS ERROR IN THE VALUE OF FORCE PEAKS REACHED AT THE MOMENT OF CONTACT WITH THE GROUND (PEAK RELATIVE TO THE HEEL) AND IN THE MOMENT OF MAXIMUM THRUST UPWARDS (PEAK RELATIVE TO THE METATARSALS). THE VALUES WERE NORMALIZED TO THE MAXIMUM VALUE OF THE PEAKS RECORDED FOR EACH TEST.

PEAK	TEST 1	TEST 2	TEST 3	TEST 4
Heel	6.60%	10.7%	15.5%	11.6%
Metatarsal	2.79%	8.84%	7.78%	4.31%

Adding channels definitely increases the availability of the information; however, it increases both system complexity and calibration procedure. The results of two experimental tests are shown in Fig 7. As it can be seen, the acquired signal by channel 2 is different (green curve in Fig 7.a and 7.b). This is

because of force platform position, runner style and the higher travel speed achieved during the second test. Another observation made always on the channel 2 is that the signal shape is irregular and noisy by increasing the speed. The results are more accurate in comparison to Fig. 6 (first configuration) due to the more accurate positioning of the sensors.

E. Third Configuration

For the third force sensors configuration, which is depicted in Fig. 5.c, it was decided to follow the approach used in [16], and to remove the central sensor in order to have a better coverage forefoot. The aim is to detect more accurately the impulsive force peaks.

The applied changes in the third configuration are modification of the position of sensor 2 (see the Fig. 5.c) and placement of all the sensors on the independent channels (totally 5 channels).

F. Procedure

The tests for data acquisition have been done based on third configuration in this way: force platform was placed in a running track (in a proper position compared to the level of the ground) and the reaction force exerted by four different tests (subjects) have been recorded and registered. Every test has registered totally fifteen steps, this is to understand how the coefficient may be varied depending on the work condition.

TABLE I V

COEFFICIENT CALCULATED TO MINIMIZE THE RMS VALUE OF THE ERROR BETWEEN THE FORCE PEAKS REGISTERED AND RECORDED WITH FSR SENSORS AND THE FORCE PLATFORM K_{PEAKS}. THE MEASUREMENT UNIT IS $\left[\frac{N}{LSB}\right]$.

CHANNEL (Heel)	TEST 1	TEST 2	TEST 3	TEST 4
1	2.85	0	0.4	2
2	7.88	44.1	54.5	11.7
CHANNEL (Metatarsal)	**TEST 1**	**TEST 2**	**TEST 3**	**TEST 4**
2	1.60	0	1.08	0.35
3	3.18	2.26	1.06	1.90
4	2.39	0.24	2.17	0
5	4.47	0	1.49	7.45

Two types of coefficients were calculated with the linear regression. The first set of coefficients is chosen in order to minimize the error between the extracted curves from the force platform and the sensors, and have been calculated by appending the various tests carried out by the same person and also by applying linear regression to the whole performance of all the steps. The second set of coefficients is targeted instead of minimizing the error on the two characteristics peaks of GRF in a way similar to what was done for the first set of coefficients.

For the first peak, which shows the pressure at the moment of heel contact with the ground, channels 1 and 2 (see Fig. 5.c) is considered and for the second peak, which realizes the exerted force of metatarsals the channels 2, 3, 4 and 5 is taken into account.

This procedure is performed independently for each test. Fig. 7 shows some test results. In particular, the figure refers to the obtained performance with the coefficient that minimize the RMS value of them error signal between the registered force by the force platform and the sensors (this set of coefficient will be K_{graph}).

G. Results

Although these results seems be worse respect to the second configuration it should be taken into account that these results are extracted from 15 steps and not the two first steps of the tests. The calculated coefficient are given in Table II. From these data. We can definitely say that the coefficient vary greatly among each singular test.

Another important observation is that some coefficients are zero, this means that the corresponding channel does not bring any additional information with referring to other channels.

The results are obtained using the second set of coefficient (K_{peaks}), those that minimize the error relating only to the peaks of the curve, are summarized in the Fig. 8 and 9.

The graphs represent the force peaks (on the heel and metatarsals) recorded by the FSR sensors and each point is related to a test. In all cases, we see the trend monotonically increasing (as was expected) showing a certain linearity between the measured force and the exerted force, however, we see that the dispersion of the points is very wide between the tests. The RMS value of the error of these measurement was normalized to the maximum force peak recorded and registered by the force platform from the heel and metatarsals for every test. The results for every test are reported in Table III.

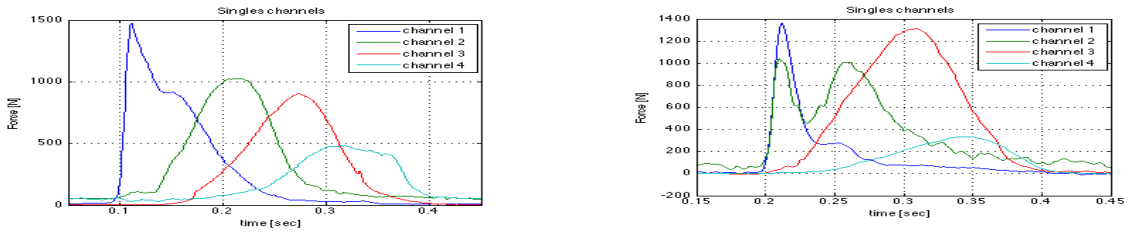
The average value of the RMS error (considering both peaks) is about 8.5%, which is a result not far from the 5% accuracy which was the target of the system. The set of coefficient calculated on the basis of the force peaks are reported in Table IV.

VI. CONCLUSION

In this work an economic mechatronic system mounted on insole in order to measure accurately the vertical forces for the human gait analysis has been realized and presented. While almost the similar systems has dealt with analysis of the walk, in the presented system race forces which conclude higher and more impulsive nature, are also involved.

Laminar FSR sensors have been placed on the insole of the shoe, it was seen that the sensor positions is an important factor in final results. Moreover, it was concluded that high number of sensors will not necessarily increase the accuracy of the system.

The main aspects that have characterized in this work are: Choices of the sensors, physical realization of the prototype in a reliable compact, arrangement of the sensors on the insole in order to obtain the maximum amount of information as possible and Sensor calibration.

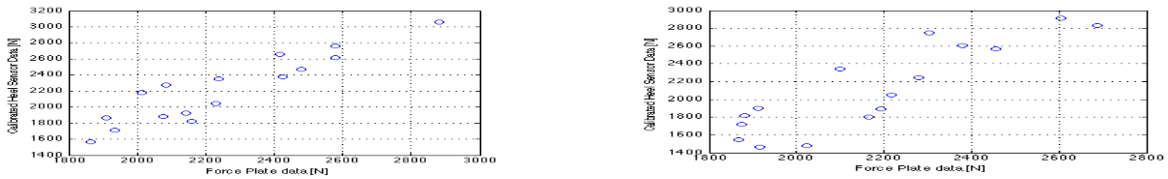


(a) (b)

Fig. 7. Data acquisition with the second configuration of two different tests. Total number of channels weighted to reduce the RMS value of the error between two curves. (a-b) performance of individual channels

(a) (b)

Fig. 8. Acquired signals from two tests. Recorded track process by the force platform (in blue) and that of the calibrated sensors for reducing the RMS value of the error signal between two curves. Here only two steps are shown but totally 15 steps exists for every test.



(a) (b)

Fig. 9. Peak forces on the heel which are measured by the FSR sensors and actual measured with the force platform. Monotonically trend increasing is clear.

Particularly, the most important features of our system are the parameterization of the force curves and possibility of reconstructing the overall trend described by the parameterized curve.

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