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Piezoelectric-based insole for gait analysis

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Abstract: *This paper presents an insole made of silicone-based material consisting of four piezoelectric sensors, each of which positioned on the following locations: toe, inner and outer positions of the foot, and heel. This insole serves to identify the gait behavior of Parkinson's disease patients. The first tests with the insole were promising, due to its possibility of obtaining signals of different magnitudes, according to the position of each sensor. The sensor positioned at the heel presented higher magnitude of signal, followed by those positioned at the toe, internal part and external part of the foot.*

1 INTRODUCTION

Parkinson's disease (PD) is a degenerative pathology that attacks the central nervous system in a progressive and irreversible way. Its main characteristics are trembling, stiffness, postural instability among others. This trembling can be characterized by random and involuntary movements caused by the reduction of dopamine, which is an assisting neurotransmitter of the voluntary movements of the human body [1]. PD affects one in every 1,000 people in the general population [2], and it is estimated that 1% of the world population over 65 years of age is affected by the disease [3]. Several scales have been developed in the last decades to evaluate the PD: Northwestern University Disability Scale (NUDS) [4], Sydney Scale [5], Parkinson's Activity Scale (PAS) [6]. Among the various parameters used in these scales the gait is one of the main parameters to evaluate the stage of disease progression. To characterize the gait of people with PD, an insole was built with piezoelectric sensors that, when a force is applied in some determined points of the insole, it is possible to correlate the intensity of the insole's deformation signal to the gait behavior of PD patients.

2 CONCEPTS

Piezoelectric sensors are based on piezoelectricity, a subclass of the electroactive properties of materials. The piezoelectric properties are correlated with the crystalline and chemical structures of the material. It can be said that piezoelectricity defines the ability of a crystalline material to generate electric current when it is subjected to a mechanical deformation. In Fig. 1 it is possible to observe an example of a crystalline structure of a piezoelectric material before and after undergoing the application of a force and its consequent deformation. Prior to the application of the force, the material is resting, and therefore the centers of gravity of the positive and negative charges in each molecule coincide, thus resulting in mutual cancellation of the effect of positive and negative charges. In such a condition, the molecule is electrically neutral. However, the deformation of the material after the application of a force results in the separation of the centers of gravity of the positive and negative charges, resulting in a molecular dipole. It can be seen that the inner poles of adjacent molecules cancel each other out, resulting in a charge distribution on the surface of the material. Thus, the material is polarized and, simultaneously, an electric field is generated, which produces a current when a load is connected at the ends of the material. It is possible to establish a relation between the deformation of the material and the intensity of the electric field generated. It is also noted that, when the force ceases, the molecular charges return to the initial positions. During the return time to the initial positions, there is a current in reverse direction of equal value flowing in the load. A characteristic of this effect is its reversibility, which is the deformation of the material when a voltage is applied. The piezoelectric effect predominates in crystalline materials such as quartz and Rochelle's salt, as well as some types of ceramics and polymers (such as polyvinylidene poly-fluoride, PVDF) [7].

(a) (b)

Fig. 1. Example of crystalline structure of a piezoelectric material: (a) before application of a force; (b) after application of a force [7].

In Fig. 2 it is possible to visualize the charge accumulation on the opposite surfaces of a piezoelectric material in response to the deformation caused by the pair of applied forces.

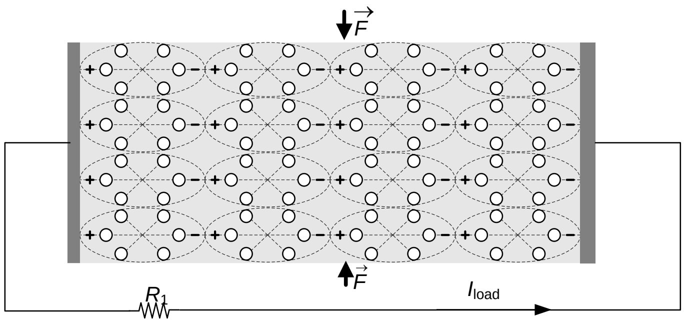
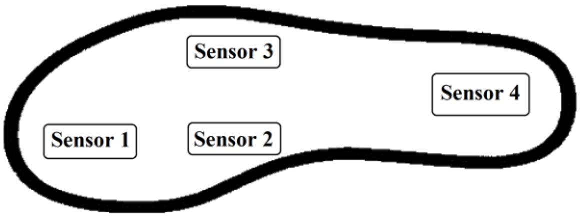


Fig. 2. Surface of polarized piezoelectric material after being subjected to an applied force [7].

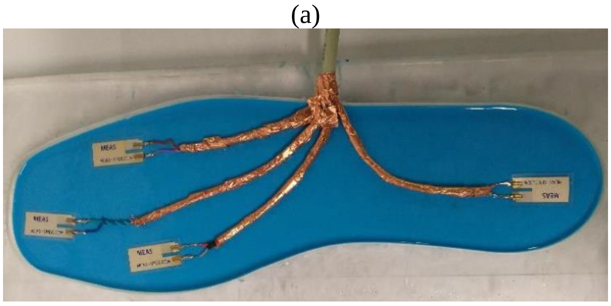
3 METHODOLOGY AND PROTOTYPE

The insole was built using a silicone rubber with density of 1298.7 kg/m^3 and Shore hardness type A equal 14. An eight meters long cable was used to connect the oscilloscope to obtain the signals of the 4 piezoelectric sensors, each one on the following positions: position 1 (Sensor 1 – Toe), internal position of the foot (Sensor 2 – Lateral forefoot), external foot position (Sensor 3 – Medial forefoot), and heel position (Sensor 4 – Foot heel). The insole was built in two steps: the first step was molding a layer of silicone until drying. After partial curing, the sensors were fixed in their respective positions, and then a second layer of silicone was placed over the preceding layer. The insole was about 12 mm thick when finished. Figs. 3(a) and (b) show the schematic concept of the insole with the position of the sensors and respective photography (before totally filling with blue silicon), respectively.

During the first tests to acquire the insole's signals on the oscilloscope, an interference of a 60 Hz harmonics signal from the power grid was observed. To suppress this noise in the signal, a passive notch filter was built with the following values of resistance and capacitance: R=1.2MΩ and C=1.2nF. Figs. 4(a) show the schematic of the notch filter and a photograph showing a bank composed by eight individual notch filters, respectively.

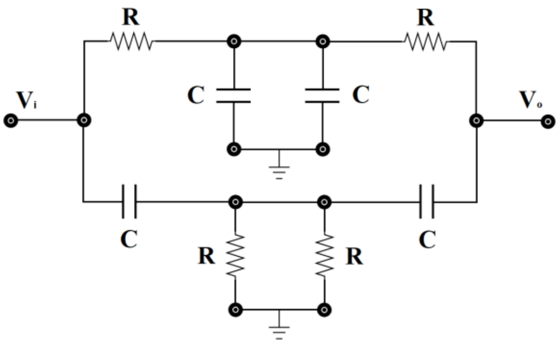


(a)



(b)

Fig. 3. For the right foot: (a) insole schematic concept, and (b) prototype photograph.



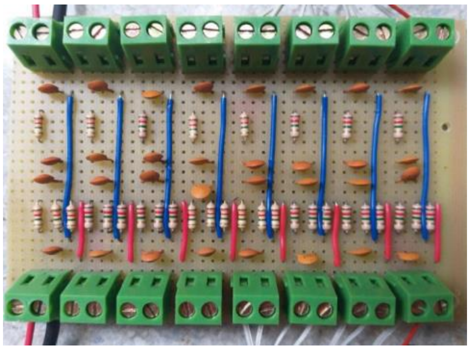


Fig. 4. Schematic of a passive notch filter for 60 Hz and a photography showing a bank with eight notch filters.

By using the passive filter, the 60 Hz interference was eliminated from the signal. Thus, the system diagram can be visualized in Fig. 5.

Fig. 5. Diagram for acquiring signs of the insole.

4 RESULTS

Few tests were done [with the insole on the right foot] on a running machine treadmill with a constant walking speed of 2km/h, e.g., equivalent to a normal walking. The signals were acquired with a module model NI PXIe-6361 from the National Instruments. The signals were acquired with a sample rate of 200SPS. The photography of Fig. 6(a) shows the PXI rack model NI PXIe-1071 with the complete acquisition system, while the Fig. 6(b) shows a zoomed photography of the acquisition module model NI PXIe-6361. Fig. 7 shows photographs of the test conditions on the running machine treadmill.

(a)

(b)

Fig. 6. Photographs of the complete acquisition system and of the acquisition module model NI PXIe-6361.

Fig. 7. Tests carried-out with the National Instruments module: (on left) View of the test condition and (on right) view of the test in detail of the feet with the proposed insole on the right foot. The insole in the left foot is outside of the focus of this paper and was fabricated using piezoelectrets sensors.

The diagram in Fig 8 illustrates the acquisition of the insole's data. The passive notch filter is used to suppress the noise at 60Hz. A healthy subject performed a gait protocol in order to measure values of voltage amplitude of each of the insole's sensors across time. The signal was obtained for each one of the four sensors, according to the schematic of Fig. 3. The subject walked on a treadmill for several minutes in order to generate regular gait cycles. Although a 6 seconds interval was used for data analysis. Fig. 8 shows the filtered and raw data for the right lateral forefoot (sensor 1). The maximum and minimum values were +467mV and -505mV respectively.

Fig. 9 shows the filtered and raw data for the right toe (sensor 2). The maximum and minimum values were 577mV and -634mV respectively.

Fig. 10 shows the filtered and raw data for the right medial forefoot (sensor 3). The maximum and minimum values were +390mV and -394mV respectively.

Fig. 11 shows the filtered and raw data for the right heel (sensor 4). The maximum and minimum values were +1948mV and -886mV respectively.

Fig. 12 shows the filtered data from all the sensors of the insole. Finally, Table I summarizes the maximum and minimum values for all sensors.

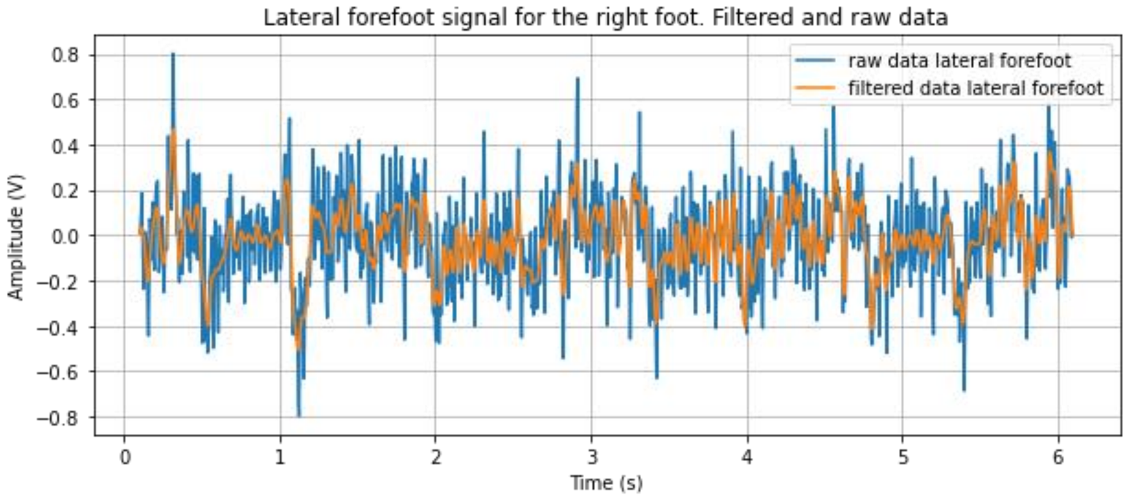


Fig. 8. Lateral forefoot signal for the right foot.

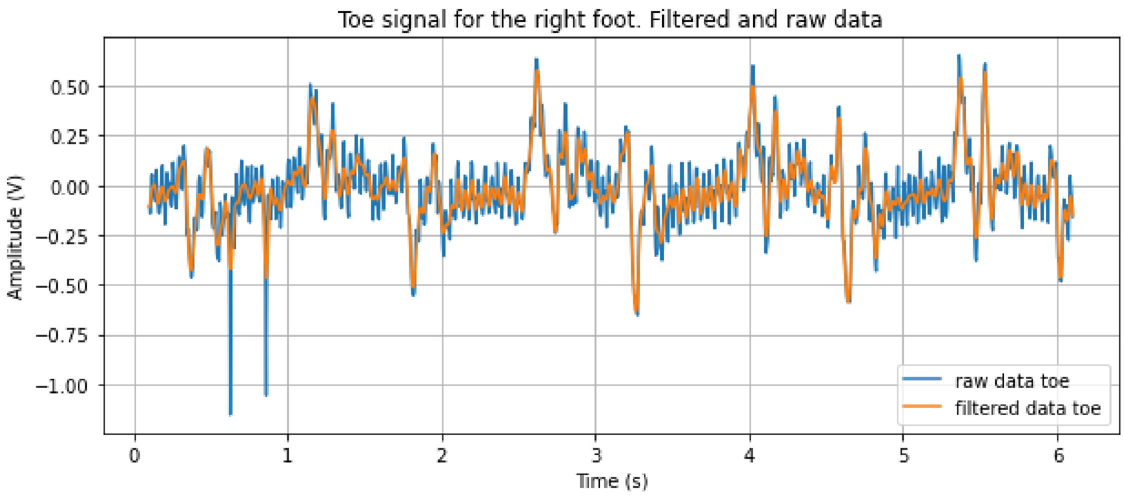


Fig. 9. Toe signal for the right foot.

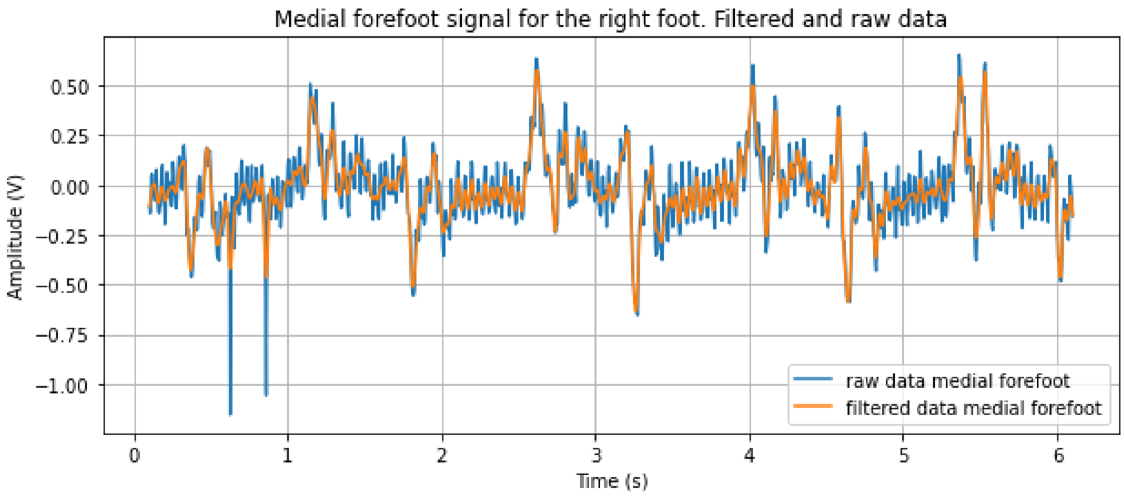


Fig. 10. Medial forefoot signal for the right foot.

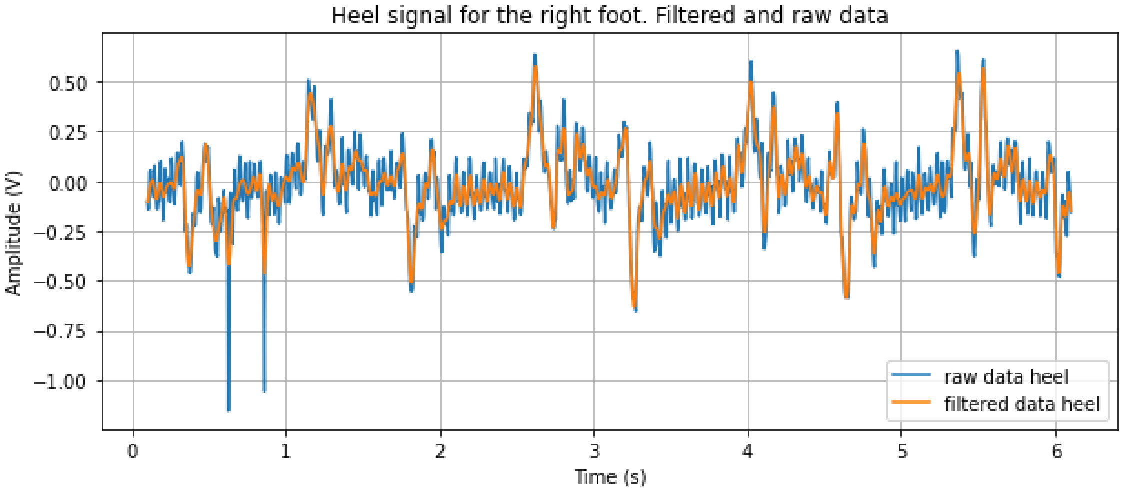


Fig. 11. Heel signal for the right foot.

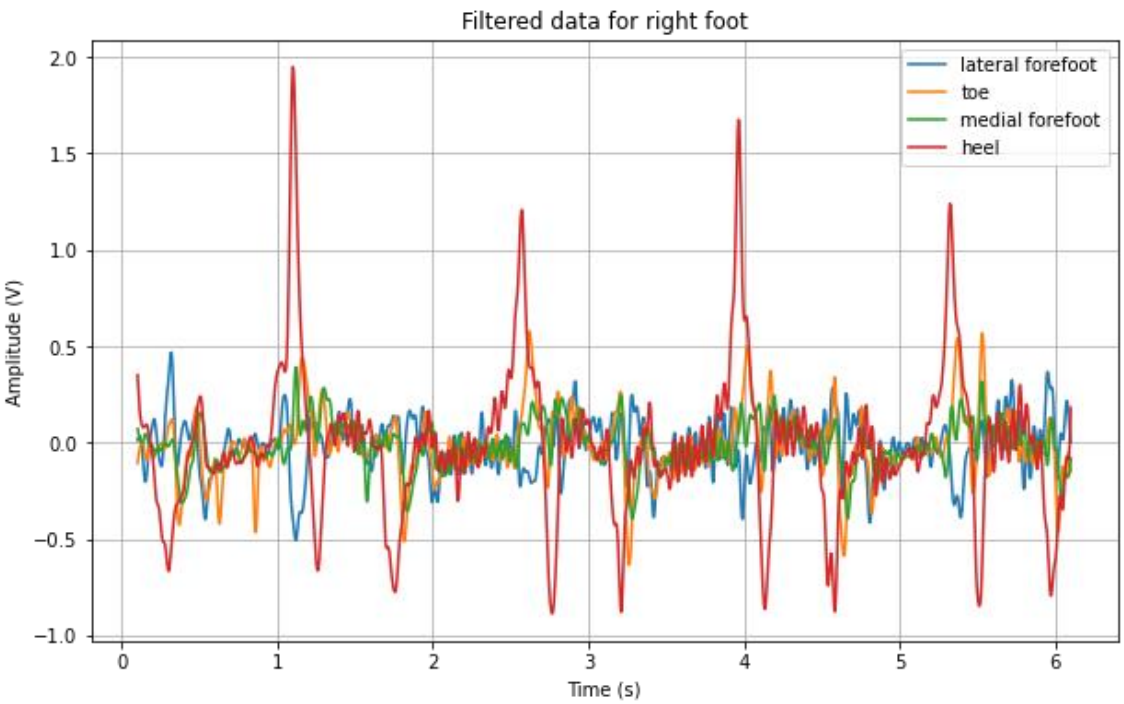


Fig. 12. Filtered data for right foot.

TABLE I OUTPUT SIGNAL OF THE SENSORS AND ITS AMPLITUDES.

Sensor	Positive amplitude[a] [mV]	Negative amplitude[b] [mV]
Lateral Forefoot	467	-505
Toe	577	-634
Medial Forefoot	390	-394
Hell	1948	-886

5 CONCLUSIONS

Figures 9 to 12 shows that the notch filter could successfully handle the high frequency noises. Positive values of amplitude indicate compression of sensor whereas negative values indicate decompression of sensor. The largest amplitude was 2834mV and it was detected by the heel sensor. The lowest amplitude was 784mV and it was detected by the medial forefoot sensor. Notably the heel compression sensor could be used to indicate the beginning and ending of a gait cycle. Also, the sensors located near the toe (lateral and medial forefoot) were compressed almost simultaneously. Future research should include protocols that compress these sensors separately.

For future works, it is intended to develop an electronic board to be connected to the insole, which will comprise the acquisition, filtering, amplification, and transmission of the signal by a wireless network to a computer, according to the schematic on Fig. 13.

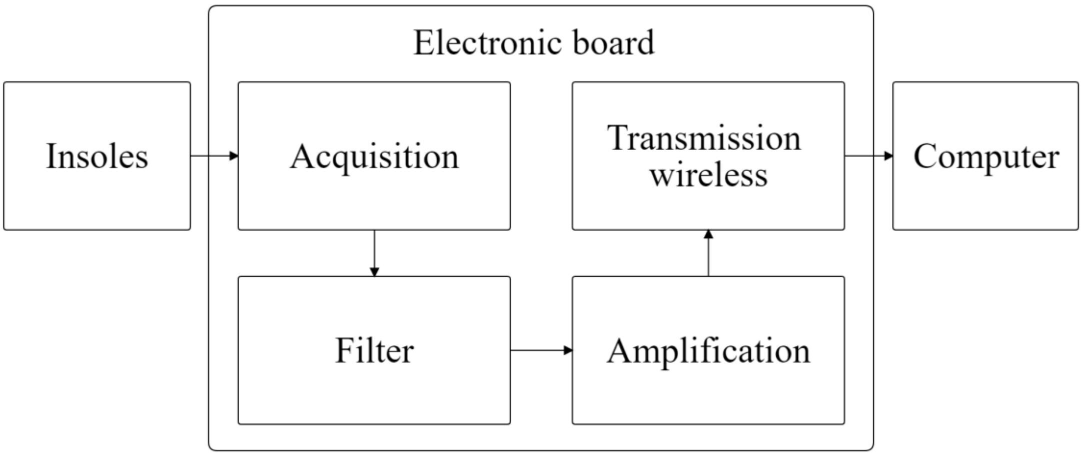


Fig. 13. Electronic board schematic.

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