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Footstep Classification Methodology using Piezoelectric Sensors Embedded in Insole

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***Keywords*—Smart insole, piezoelectric sensor, foot posture, footstep types.**

***Abstract*— This article presents a proposal for a methodology to classify the types of steps, using piezoelectric sensors embedded in an ethylene-vinyl acetate (EVA) insole, configuring a low-cost intelligent insole. From a few steps or a walk by the user, the electrical signals generated by the piezoelectric sensors are measured or stored for later treatment and analysis. The steps of the proposed methodology were applied step by step in tests carried out to classify the types of footsteps of male and female users, who used the intelligent insoles built into running shoes. The proposed methodology was also implemented in a computational code that was applied to classify the types of steps in the performed tests. The step classification results were satisfactory, compared with the specialized literature. It should be noted that the classification obtained from the application of the methodology is a suggestion of the type of footfall from an engineering point of view, and the result should be evaluated by a specialized health professional.*

I. INTRODUCTION

Daily walking, the need to stand for a long period of time, performing physical activity, combined with the person's weight, demand energy consumption and great physical effort. In humans, the feet are of fundamental importance in locomotion, weight support and body balance. The basic mechanics of moving the foot's center of mass during walking or running are similar in mammals of different body sizes, but whereas most mammals contact the ground only with their fingers or the tips of their toes, humans and great apes are plantigrade, bringing the whole foot down, including the heel, as shown in the illustration of the human foot in Fig. 1 [1]. When starting the displacement, the main movements of the foot, shown in the lower part of Fig. 1, are: touch of the hindfoot on the ground (heel), followed, almost immediately, with the sole of the foot (plantar fascia) in a flat position on the ground supporting the body on the midfoot and, finally, the forefoot supporting the body, lifting the heel and levering the toes.

Recent experimental studies show that human foot posture has important biomechanical implications on foot strike and thrust during walking and running. In general, the human foot model used for studies focuses on three major kinematic challenges of walking and running: (1) how the foot deals with impact forces when the lower extremity initially collides with the ground; (2) how the foot creates propulsive leverage for propulsion and (3) how the foot stores and releases elastic energy during running [1]. For a better analysis of plantar pressures, the sole of the foot can be divided into 15 anatomical areas, as shown in Fig. 2 [2], in which the heel corresponds to areas 1 to 3, the midfoot to areas 4 and 5, the metatarsus to areas 6 to 10 and the toes to areas 11 to 15. The enclosed areas support most of the weight and adjust the body balance. The strength measured in these positions can be used to obtain physiological, structural and functional information on the lower limbs and the entire body. Running or walking, is a series of pronations and supinations that occur in the feet. Running is distinguished from walking by the increase in speed, or distance covered per unit of time, and by the presence of a hovering or airborne phase. In this sense, studies and methods have been and are being developed to help professionals who deal with the biomechanics of the foot, as well as users in general, in order to identify the type of step, assess the posture of the foot and whether there is any irregularity in it [3]. structural and functional aspects of the lower limbs and the entire body. Running or walking, is a series of pronations and supinations that occur in the feet. Running is distinguished from walking by the increase in speed, or distance covered per unit of time, and by the presence of a hovering or airborne phase. In this sense, studies and methods have been and are being developed to help professionals who deal with the biomechanics of the foot, as well as users in general, in order to identify the type of step, assess the posture of the foot and whether there is any irregularity in it [3]. structural and functional aspects of the lower limbs and the entire body. Running or walking, is a series of pronations and supinations that occur in the feet. Running is distinguished from walking by the increase in speed, or distance covered per unit of time, and by the presence of a hovering or airborne phase. In this sense, studies and methods have been and are being developed to help professionals who deal with the biomechanics of the foot, as well as users in general, in order to identify the type of step, assess the posture of the foot and whether there is any irregularity in it [3]. and by the presence of a floating or air phase. In this sense, studies and methods have been and are being developed to help professionals who deal with the biomechanics of the foot, as well as users in general, in order to identify the type of step, assess the posture of the foot and whether there is any irregularity in it [3]. and by the presence of a floating or air phase. In this sense, studies and methods have been and are being developed to help professionals who deal with the biomechanics of the foot, as well as users in general, in order to identify the type of step, assess the posture of the foot and whether there is any irregularity in it [3].

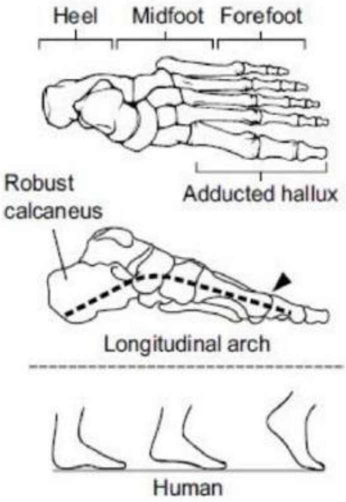

Fig. 1. Illustration of the human foot [1]

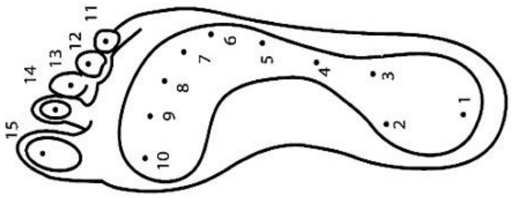

Fig.2. Anatomical areas of the foot [2]

As an example of division of the plantar fascia for evaluation and analysis of regions with higher pressure peaks, Fig. 3 eight areas that were identified [4], being the heel region (H1 and H2), metatarsal joints (M1, M2, M3, M4 and M5) and hallux (T1). As a characteristic of the supinated step, the largest area of the contact surface is on the outside of the foot, reaching up to the 5th toe, being a type of "step outside". Pronation or pronated stepping is opposite to supination, with greater contact intensity on the inner edge of the foot, including the hallux toe, characterizing an "inward step". The normal gait (flat or neutral) is characterized by a wide area of contact between the plantar fascia and the ground. In Fig. 4 shows illustrations of types of supinated, normal and pronated foot on a right foot [5].

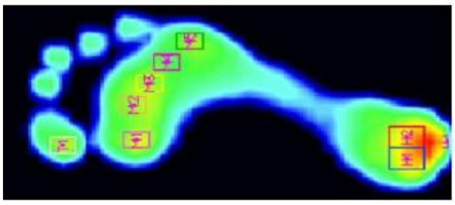

Fig. 3. Eight pressure areas on the foot [4]

Studies of plantar pressure patterns in a static position and in movement of the feet are carried out with the aim of evaluating and/or classifying the type of foot by specialists in the areas of health and sports activity. Accurate and reliable measurements are taken of various movement parameters such as contact and non-contact times, pressure distribution and plantar force, gait symmetry, acceleration and orientation of foot movements which allow walking patterns to be classified as normal or pathological [6]. Gait is a sequence of periodic events characterized as repetitive cycles for each foot, with each cycle divided into two phases, as shown in Fig. 5 [7]. The feet make recurrent contact with the ground surface to move the trunk and lower limbs in a coordinated manner, providing a change in the position of the center of mass of the body. The gait phases are summarized below [7]:

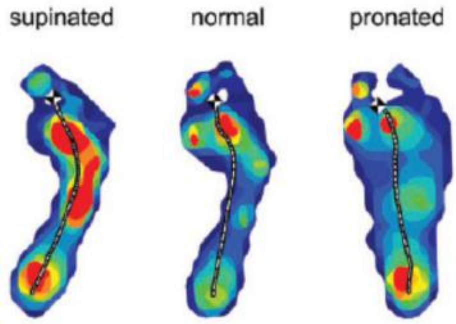

Fig. 4. Supine, normal and prone footfalls [5]

a) Support Phase: foot in contact with the ground. This phase is subdivided into four intervals: heel contact with the ground (A), flat foot contact with the ground (B), medium stance, when the body rests on one foot (C) and when the heel lifts (D);

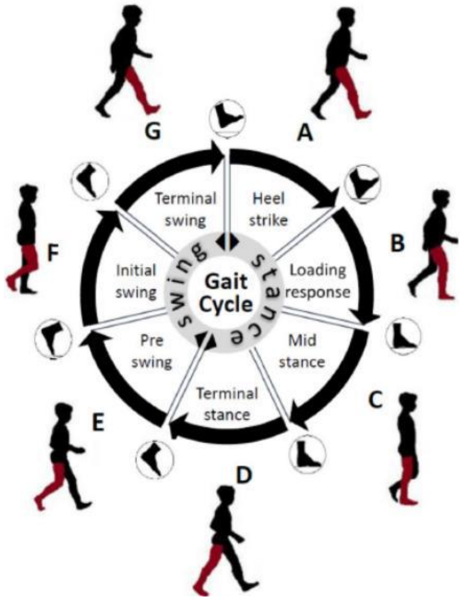

Fig. 5. Gait cycles [7]

b) Balance Phase: foot dangling, not in contact with the ground. This phase is subdivided into three intervals: pre-swing, which occurs with initial hip flexion (E), initial swing when body weight is shifted to the opposite forefoot (F), and terminal swing, which is the last interval of the cycle. of gait, initially with maximum knee flexion and ending with maximum forward oscillating hip extension (G).

Traditionally, the study of gait events has been based on the analysis of plantar pressure. A notable development in this field is a shoe-integrated sensor system for wireless gait analysis and real-time feedback, in which spatial pressure distribution and foot acceleration are used for pattern recognition and numerical analysis [6]. In [7] gait parameters are listed to be analyzed in clinical health settings:

-Cadence or pace (number of steps per unit of time);
- Stride length;
-Speed;
-Direction of leg segments;
- Pitch angle;
-Swing time for each foot;
-Step width;
-Support time;
-Ground Reaction Force (GRF);
-Electrical activity produced by muscles;
- Moment and forces;
-Body posture.

The foot posture assessment and gait analysis resources are used to classify the type of foot or stepping, for example, based on plantar pressure signals or tensions generated by electrical sensors, positioned at strategic points in the smart insole. The signals produced by the sensors are captured by a data acquisition system and transmitted in real time to a processing center equipped with artificial intelligence, which analyzes and classifies the type of foot and/or footfall of the user. According to [7], different foot type classification methods have been used, making it impossible to compare results and obtain safe conclusions. One classification method combines structural data with information about foot function under dynamic load situations, should relate to the functional behavior of the foot during locomotion. There is still no consensus on an ideal method for classifying foot type. The existing methods are typically based on the measurement of morphological parameters of the foot, mainly in the static position of supporting the body or during locomotion. Foot type classification methods based on their morphology can be classified into one of the following categories [8]:

- Non-quantitative visual inspection;
- Anthropometric values;
- Step parameters;
- Radiographic evaluation.

The objective of this article is to present a proposed methodology to classify the type of stepping using piezoelectric sensors embedded in an EVA material insole, therefore a low-cost intelligent insole. In this context, the works presented from this paragraph are consistent with the objective of the proposed methodology. The assessment of posture and classification of the foot/tread can be started from printing the plantar fascia in ink or using electrical or pressure transducers embedded in insoles, and it may be possible to include the data set obtained from the sensors, the measurement of the width or area of contact between the soles of the feet and the ground [8].

According to [9] around 81 prototypes of intelligent insoles have already been developed in research carried out, in addition to 15 commercial products used in three groups of studies: gait evaluation, totaling 70.93%; recognition of activities (17.44%) and other studies (11.63%). Smart insoles began to gain prominence in 2008, thanks to the emerging technology of flexible electronics and flexible printed circuit boards (PCBs), as shown in the timeline shown in Fig. 6. Most smart insoles use various types of sensors, collecting information such as movement, environmental data and location.

In general, the development of machine learning and sensor fusion technologies provided solutions for the massive processing of the sensors used, which can be positioned in different regions of the feet. From 2014, smart insoles have gained increasing attention from researchers and industry with application in people's everyday and popular life, due to factors: mature technologies employed in recent years, continuous simplification of smart insole designs, signal processing algorithms with advanced machine learning technologies and new sensor technologies. Since then, various types of sensors have been used in smart insoles such as gait event detection, gait analysis with wearable devices and sensory signal processing,

As a technique for evaluating and classifying the type of foot, baropodometry is used, which uses a platform-type base with sensors and software for analyzing plantar pressure through the recording of footprints and ground reaction forces. One way to evaluate the regions of the feet, rearfoot, midfoot and forefoot, is with the person in an erect and static posture, which allows determining the percentage of weight supported by each foot, the symmetry relationship between them and the calculation of the index of weight. arch depending on the type of foot: normal, cavus or flat. Postural abnormalities of the feet can be detected by correctly evaluating the feet and can be treated, as suggested by several authors, by strengthening and stretching the postural muscles and/or using insoles [10].

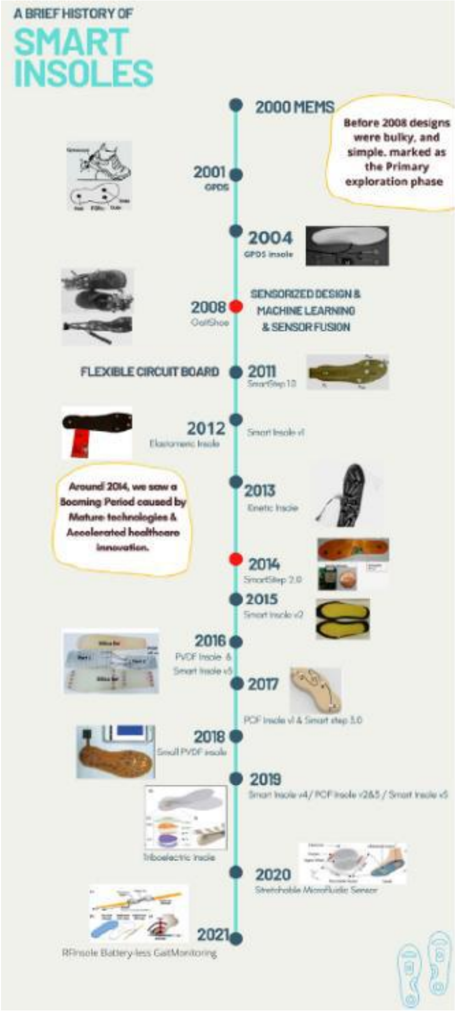

Fig. 6. Smart insole technology [9]

Two main types of plantar pressure sensors are used in baropodometers: resistive and capacitive. In resistive sensors, the flow of electric current occurs when pressure is exerted on the surface of the sensor, causing the contact resistance to change. Capacitive sensors are based on the inverse variation of the thickness of an elastic material and, due to the pressure exerted on the sensor, a proportional and linear increase in capacitance occurs. However, fast measurement of capacitance is not as easy as resistance and moreover having high impedance in case of small capacitors can be produce noise and interference problems in capacitive sensor [10].

II. METHODOLOGY

Based on technical and documentary bibliographical research, experimental tests carried out in the field and data collection, this article presents a proposed methodology for classifying the types of footfall, using piezoelectric sensors embedded in an EVA insole, configuring a low-cost intelligent insole. Other important quantities in the analysis of the type of footfall are the force and pressures distributed in the sensor positioning areas.

Measurement of plantar pressure is not commonly performed in a clinical setting. Even in research projects, this practice is little used, although its potential is well recognized in the specialized scientific literature. One reason for this could be a certain lack of accuracy in baropodometers, the causes of which could be: sensor technology; matrix spatial resolution; pressure variation; sampling rate; calibration procedures; post-processing and legacy data [10]. In the research carried out, few used the baropodometer and, in addition, most articles do not present the measured pressure values and, in those that show these values, there are significant discrepancies in the indication of similar pathologies, population samples and comparable experimental settings [10].

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There are several purposes and types of sensors used in smart insoles: detection of gait events with wearable devices, work activities, processing of sensory signals, etc. The most common sensors are force and pressure sensors, such as force sensing resistors (FSR), piezoelectric force sensors (PFS), capacitive sensors (CS), air pressure sensors (APS) and opto pressure sensors. (OPS) [9]. In the tests carried out in this research, piezoelectric sensors (PFS) were used, which are small, available in some sizes (circular), wide measurement range, support high weights and, in addition, low cost.

In Fig. 7 shows an illustration of an intelligent insole with a data acquisition/transmission system and a 15 mm diameter piezoelectric sensor. Some disadvantages of these sensors are: not suitable for static measurements, may present false measurements due to vibrations and applied forces, may fail when used for a long period and there is a need for an electronic system for acquiring the signals [9].

Fig. 7. Data acquisition/transmission and PFS sensor

The steps of the proposed methodology for classifying footfall types are described in a simplified flowchart in Fig. 8. Attention should be paid to the importance of the video/measurement analysis stage, as if any inconsistency is found, the foot test must be repeated. The application of the methodology was carried out manually, that is, analytically, and automatically, using a computational code that was implemented in Python.

III. RESULTS AND DISCUSSION

The walking tests were carried out in an external environment with male and female users and without knowledge of their type of footfall. In order to carry out the tests, smart insoles, left and right, with nine piezoelectric sensors, were embedded in running shoes. In Fig. 9 shows an illustration of insoles with the numbering of the sensors and a pair of insoles 36 used in the stepping tests. Tests were carried out on insoles 36, 37, 39, 41, 42 and 44, but in this article, the tests on insoles numbers 36, 42 and 44 will be described.

The stepping test using the pair of insoles 36 was performed by a woman. In Fig. 10 shows the pair of insoles 36 embedded in sneakers and an illustration of the type of pronated stepping, in which the sensors in red have a greater magnitude of voltage than the yellow ones and sensor 5 has not been activated.

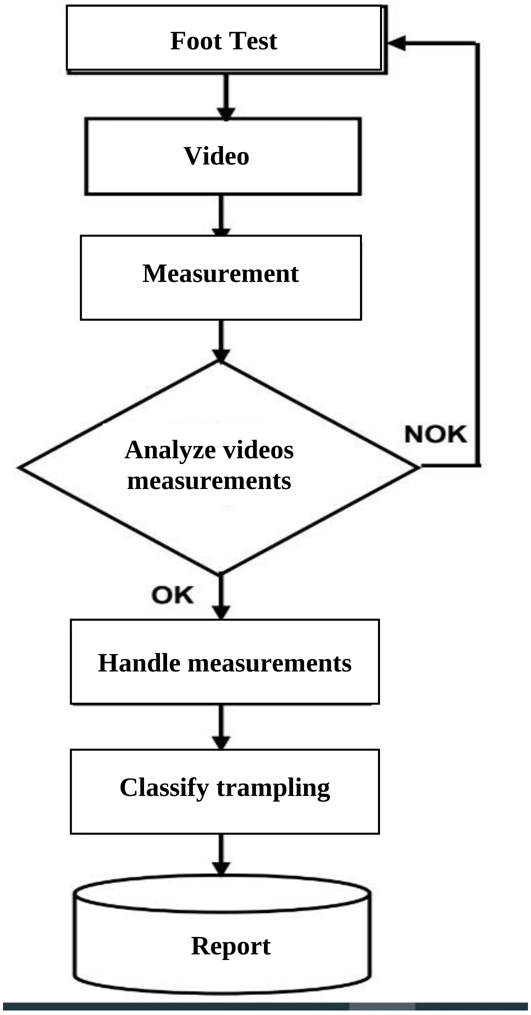

Fig. 8. Flowchart of the proposed methodology

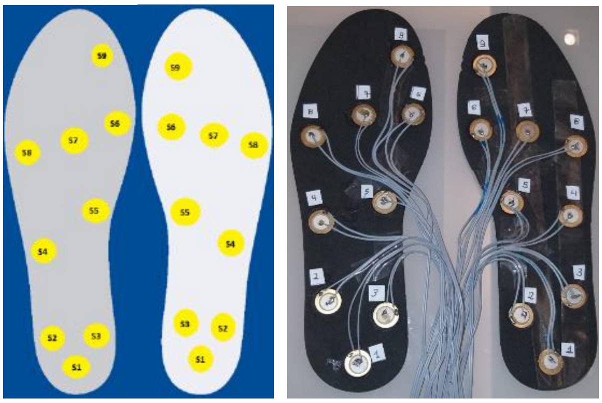

Fig. 9. Numbering of sensors and insoles 36

The voltage values generated by the sensors are organized in tables. Table 1 shows the maximum tension values obtained in the right insole 36. The stepping classification is carried out from the comparison of the values obtained, according to the position of the sensor. Thus, in the case of the user who participated in the test with 36 insoles, the classification of her step is***pronated***, as shown in Fig. 10, in which the sensors in red showed the highest activation values in relation to the yellow ones and sensor 5 was not activated.

Fig. 10. 36 insoles in sneakers and illustration of pronated stepping

Table. 1: Values obtained from the right insole 36

Sensor	Voltage (V)
1	1.49
2	1.59
3	1.79
4	1.28
5	0.00
6	1.42
7	1.39
8	1.50
9	1.92

Source: Author

In the stepping test carried out with the pair of insoles 42, the user was a man. In Fig. 11 shows the insoles used in walking and an illustration of the type of supinated step. As in the previous experiment, a thin EVA insole was placed over the sensors and, subsequently, the pair of insoles was embedded in sneakers. The electrical signals measured in the insoles, left and right, were tabulated for later analysis and classification of the user's step. Table 2 shows the maximum values obtained in the right insole. Thus, applying the proposed methodology for step classification, the result of the step of the user of the smart insole 42 is Supinated, as shown in Fig. 11.

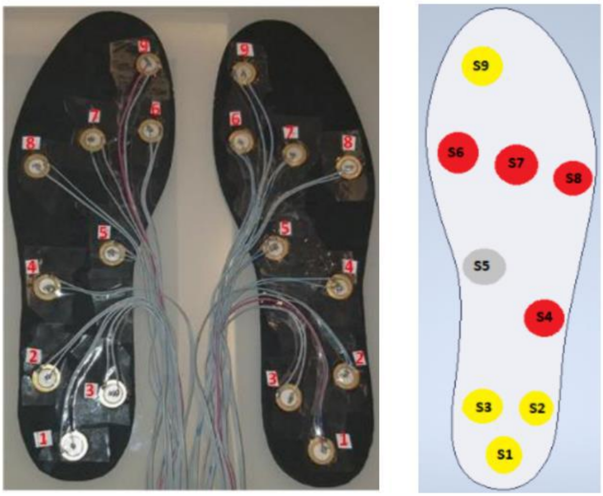

Fig. 11. Insoles 42 with nine piezoelectric sensors.

Table. 2: Values obtained from the right insole 42
Source: Authors

Sensor	**Voltage (V)**
1	1.16
2	1.21
3	1.32
4	1.44
5	0.00
6	1.49
7	1.57
8	1.83
9	1.45

The forces and pressures distributed in the areas of the sensors are magnitudes that help in decision-making regarding the posture and classification of the type of foot/step. From (1), available in [11], the force applied on the piezoelectric sensor can be calculated:

$$V_{out,PD} = \left(\frac{C_{PD}D_{PD}}{C^T_{PD}A_{EPD}}\right)F_{PD,A}$$

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Where, $V_{out,PD}$ is the voltage generated by the piezoelectric sensor, FPD,A is the force applied to the sensor, DPD is the thickness of the sensor, AEPD is a is the area of the sensor electrode, CPD is the dielectric constant of the sensor as a function of of the material and C^T_{PD} is the relative permittivity.

Subsequently, it is possible to calculate, with good approximation, the pressures at the various points. As an example, shown in Fig. 12 simulations of distributed forces, carried out in CAD Inventor software, in insole number 36-left, and insole number 42-right. In the images, according to the color palette, the highest intensities of forces can be seen on the inside of the insole 36 and on the outside of the insole 42.

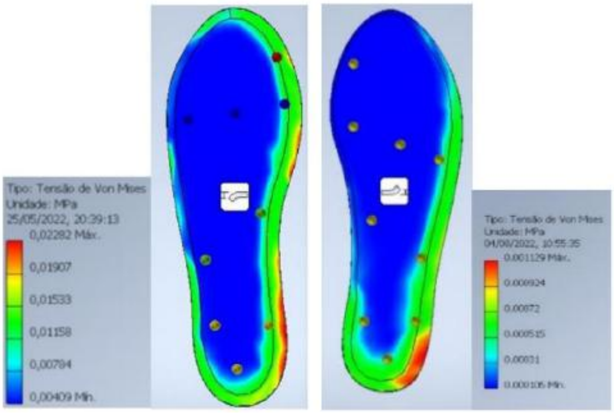

Fig. 12. Forces on insoles 36 and 42.

IV. CONCLUSION

In this article, the objective was to present a methodology for classifying the type of footfall, using a low-cost intelligent insole. In this sense, it can be concluded, according to the tests carried out, that the proposed methodology reached its objective, even considering the limitations of piezoelectric sensors. It should be considered that, due to the low cost of the smart insole, adequate quantities can be produced for replacements, when necessary. An observed fragility, which does not only occur with piezoelectric sensors, concerns the break in solder connection points of the signal acquisition conductors. This fragility was reduced by improving the welding and physical protection of the sensors.

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