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Development of an in-shoe pressure-sensitive device for gait analysis

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***Abstract*—In this work, we present the development of an in-shoe device to monitor plantar pressure distribution for gait analysis. The device consists in a matrix of 64 sensitive elements, integrated with in-shoe electronics and battery which provide an high-frequency data acquisition, wireless transmission and an average autonomy of 7 hours in continuous working mode. The device is presented along with its experimental characterization and a preliminary validation on a healthy subject.**

I. Introduction

Measurement of plantar pressure distribution is widely recognized as a key tool in clinical gait analysis (e.g. in case of gait abnormalities [1], diabetes mellitus, peripheral neuropathies and musculoskeletal disorders [2]), as well as in footwear evaluation [3], and in sport training [4][5][6].

Two types of devices are commonly used for plantar pressure monitoring: force platforms and pressure-sensitive foot insoles. The former, e.g. the EMED®-SF (Novel USA, Inc., Minneapolis, MN, USA), are high-resolution, high-frequency floor-mounted matrices of pressure sensors, which can capture three-axial pressure data of the barefoot. While these platforms are very valuable for clinical studies, they are not suitable when measurements of pressure at the shoe-foot interface are required [2], or when a high-portability is desired. To tackle these needs, pressure-sensitive foot insoles have been developed through several sensing technologies, ranging from force-sensing resistors, as in the F-Scan® system, (Tekscan Inc., Boston, MA, USA), to capacitive sensors, as in the Pedar® system (Novel GmbH, Germany) to piezo-resistive sensors, as in the paromed® (Vertriebs GmbH & Co, Neubeuern, Germany). However, most of these systems require electrical wires to connect to wireless communication modules that are strapped around the waist or the ankle of the user, causing discomfort and making long-time monitoring and recordings during daily life or sport activities difficult to obtain. For these applications, devices which fit entirely inside the shoe, with a long time autonomy, and with wireless communication are desirable. Some devices of this kind have been developed in the last years [7][8][9], tough with a reduced temporal and spatial resolution (e.g. six sensors are used in [7][9], four in [8]), and including a small-scale integrated acquisition electronics.

In this work, we present a new in-shoe device to monitor plantar pressure, consisting in a matrix of 64 sensitive elements, integrated with in-shoe conditioning electronics and battery. The device provides high-frequency data acquisition, on-board computation of center of pressure and ground reaction force, and wireless communication, with an autonomy of about 7 hours in continuous working mode. The device can replace the insole of commercially available shoes, without interfering with the normal gait. The system is presented along with an experimental characterization and a preliminary validation on a healthy subject.

II. Development of the insole hardware and software modules

Our in-shoe device comprises two hardware parts: an array of pressure sensors, and the on-board electronics for signal conditioning and wireless data transmission. The sensor array is made of 64 silicone-covered opto-electronic pressure sensors, is deputed for pressure transduction, and is connected to the on-board electronics through two flat cables carrying unamplified analog voltage signals. The on-board electronics performs high-frequency data acquisition, filtering and de-sampling, and also computes the estimated

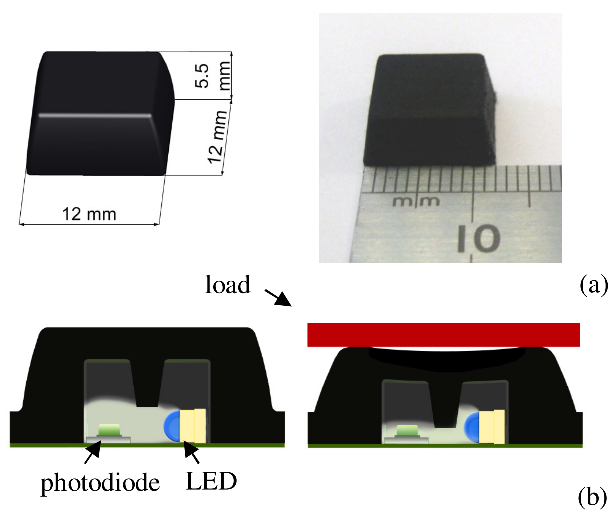

Figure 1. Base sensitive element of the pressure-sensitive insole. (a) Silicone cover of the sensitive element. (b) Representation of the transduction principle. When a load is applied (on the right), the consequent deformation of the structure occludes the light path, and results in a diminished output from the photodiode.

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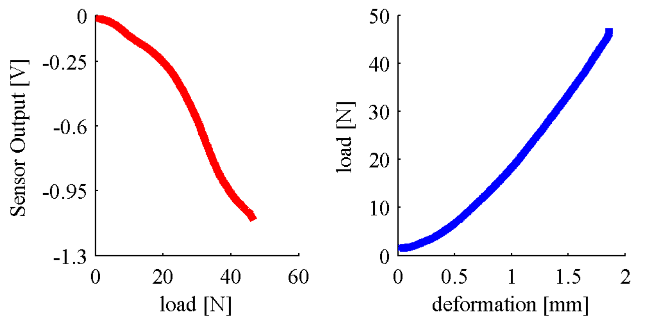


(a) (b)

Figure 2. Characterization of the sensitive element. (a) Shows the force vs. Voltage output characterization, while (b) shows the structural characterization of the sensor.

center of pressure and ground reaction force. All data is transmitted wireless at a 100 Hz frequency. The autonomy of the device in continuous working conditions is about 7 hours.

A. Sensor Array

1) Sensitive Element

The pressure sensitive element presented in this work is based on a tactile sensing technology relying on an opto-electronic transduction principle, conceptually analogous to the one presented by the authors in [10] [11] [12].

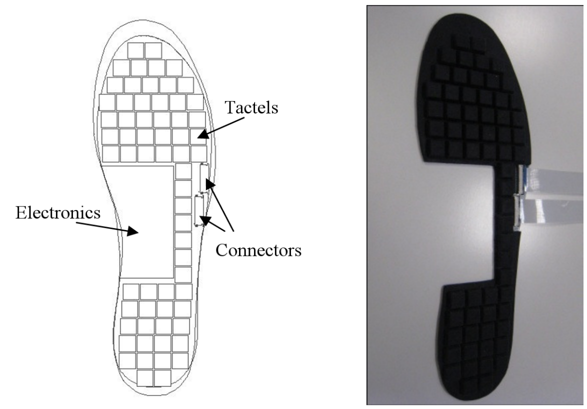
This sensitive element is made of a LED light emitter facing a photodiode as light receiver. These optical components are covered by a shell made of opaque silicone, which deforms under the effect of external force.

The sensitive element is shown in Figure 1(a). It can be seen that the sensor cover has the shape of a square pyramidal frustum, with the base having a side of 12 mm, and the top face of 10mm. This contact surface provides a $1cm^2$ resolution to the estimation of pressure distribution and center of pressure. The cover is made of a black-dyed opaque silicone.

Figure 1(b) represents the transduction principle of the sensitive element: A load applied to the top face of the cover causes a deformation, and lowers a silicone 'curtain' which obstructs the light path from the LED (on the right) to the photodiode (on the left). The sensor thus works as an inverse force vs. voltage transducer having high vertical sensitivity and low tangential sensitivity. Finally, the specific design of the cover ensure a maximum loading range of 1MPa before damaging the device.

Figure 2(a) and (b) show the characterization curve of the sensor and its structural behavior, respectively. Figure 2(a) shows the typical relationship between the applied force and the output voltage, were data was acquired in quasi-static conditions. A non-amplified dynamic output range of about 1.1V, corresponding to a 50N load on the sensor (500kPa), was observed. Notably, the maximum measurable load generates a vertical deformation of about 1.8mm. The resulting stiffness (about 28N/mm) adds compliance to the insole, increasing its comfort and wearability.

The curve in Figure 2(a) can be approximated with a third-order polynomial interpolant (see also next Section) which was found to be the best compromise in terms of complexity and goodness of fit. Further trials show that due to the rigidity of the silicone, no significant dynamic effects can be observed on the output (see [11]). Figure 2(b) portraits the structural behavior of the sensor, which shows no significant static hysteresis, and an average stiffness of 28.7N/mm.



(a) (b)

Figure 3. Sensor board. (a) Disposition of sensors, on-board electronics and connectors. (b) Picture of the sensor array complete with silicone cover and connectors.

2) Sensor Board

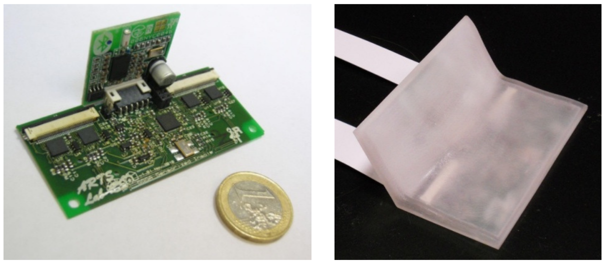
The sensor board comprises 64 sensitive, placed as in Figure 3(a). The sensitive area covers about 80% of the foot-insole contact region, leaving the Medial Arch area free from sensors, and available for the integration of the electronics. The Medial Arch area is known to be the least stressed area of the foot plant, in terms of peak pressure, mean peak pressure and average pressure during a gait cycle [13][14]. The covered area contributes to about 99% of the total pressure-time integral [13] during a gait cycle and to 100% of the pressure peaks during the gait in healthy adult subjects [13][11]. Compared to devices with fewer sensors ([7][8][9]), this insole, covering the whole interaction area, allows a direct evaluation of the center of pressure position and of the total loading force. Moreover, it permits to estimate pressure peaks with a much higher accuracy.

The sensor board is based on a thin PCB, housing, for each sensor, a power and ground wire, and a signal wire. The 64 signal channels, and the two common power and ground channels are routed through two flat cable connectors, placed in the Lateral Arch area. The cable connectors are not in contact with the foot, being positioned at a height lower than the sensors. Figure 3(b) shows the final appearance of the sensor board, complete with silicone cover for the 64 sensitive elements.

B. In-Shoe Electronics

As shown in Figure 3(a), we used the space under the *Medial Arch* area to house an in-shoe electronic board for signal acquisition, processing and wireless communication. Based on anatomical measurements, we determined the maximum encumbrance of the electronics board so as to not impact the comfort of the wearer.

The board, shown in Figure 4(a), comprises analog-digital converters (ADCs), and a microcontroller to perform signal



(a) (b)

Figure 4. In-shoe electronics. (a) without and (b) with its cover that is housed inside the shoe.

processing. The board is connected to a Bluetooth receiver/transmitter (RoboTech s.r.l., Pisa, Italy) on a UART socket. Power to the board and to the sensors is supplied by a Li-poly 700mAh battery operating at 3.6V (25x25x10mm). The board acquires the 64 signals at a 1.8kHz frequency through four 16-channels 14-bit ADCs. Signals are low-pass filtered and de-sampled to 100Hz. Each digitalized voltage is used to determine the pressure on the corresponding sensitive element through a third-order polynomial function (see Section III). The 64 pressure values are used to determine the ground reaction force on the insole and the position of the center of pressure. The pressure map (64 values), ground reaction force and center of pressure are sent at 100Hz frequency through a Bluetooth transmitter.

The power consumption of the device (sensors and electronics) is about 100 mA at 3.6-3.7V. The on-board battery can power the unit for up to 7 hours in continuous working mode.

As shown in Figure 4(b) the in-shoe electronics is protected by a rigid plastic cover, providing protection from impacts, sweating and humidity.

C. Remote Electronics and Communication

The data from the pressure-sensitive insole can be received by any remote device (PC, tablet or smarphone) equipped with a Bluetooth receiver. A 921.6Kbit/s connection is required to sustain a 100Hz communication rate. Each data packet sent from the insole includes a timestamp to verify transmission reliability on the remote host.

The remote host can command the device to initiate (or

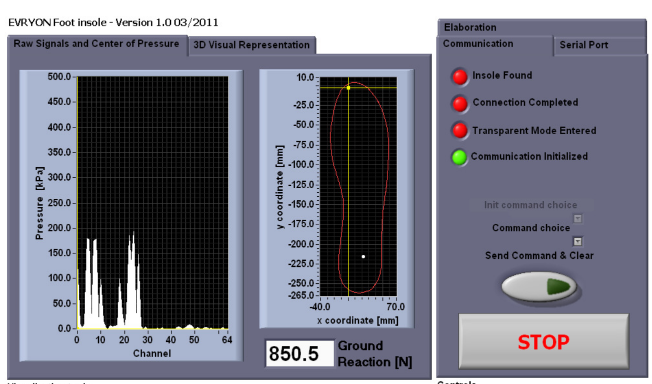


Figure 5. Graphical User Interface for the remote host.

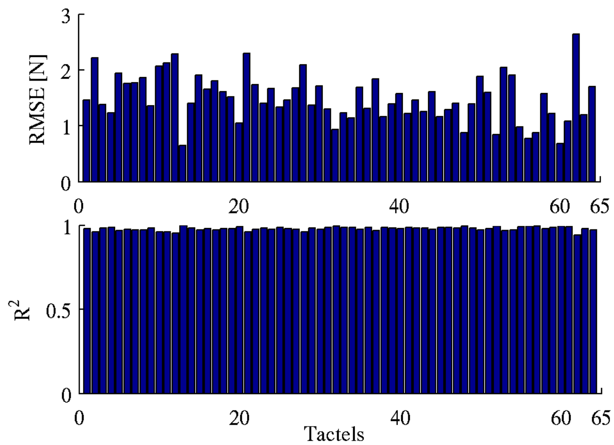


Figure 6. Characterization results. On the top, the RMSE and on the bottom, the R^2 value for each polynomial fitting.

stop) a data acquisition and communication sequence. Commands can be sent to require force de-offsetting, battery level as well as for debugging information.

D. Software Modules

We developed a graphical user interface (GUI) to allow for data monitoring and logging, as well as to remotely command the device. The interface was written using National Instruments™ Labview® 2010, and is shown in Figure 5. The GUI gives a real-time monitoring of the foot pressure map, of the ground reaction force trend, and of the position of the center of pressure. Taking into account that no computation is required from the remote host side (all calculations are done on-board), similar interfaces could be developed for less powerful architectures like tablets or smartphones.

III. Characterization of the Pressure-Sensitive Array

While all the sensors of the array have identical electronic components and silicone covering, the imprecision of the silicone molding and polymerization process, along with the variability in the characteristics of LEDs and photodiodes require a separated characterization for each pressure-sensitive element.

Characterization was performed using a three-axial robotic platform able to provide controlled loads or deformations to any given position. Each sensitive element was compressed to a maximum reaction force value of 50N, and then unloaded at a constant speed of $5 mm \cdot min^{-1}$ to give a quasi-static condition. Three loading-unloading cycles were performed for each sensitive element.

The force vs. voltage behavior was characterized for each element, with a result similar to that depicted in Figure 1(a). The curve was fitted with a third-order polynomial, unique for each sensitive element. Figure 6(a) and (b) show the results of the characterization of each element in terms of goodness of fit (R^2 and RMSE). It can be seen that a third order polynomial approximant introduces errors between 2 and 5% of the full-scale range, and that goodness of fit is high (minimum R^2 95%).

The polynomial coefficients are loaded on the firmware of the processing electronics, and allow for force/pressure estimation on each sensitive element to be performed on-board.

IV. Validation

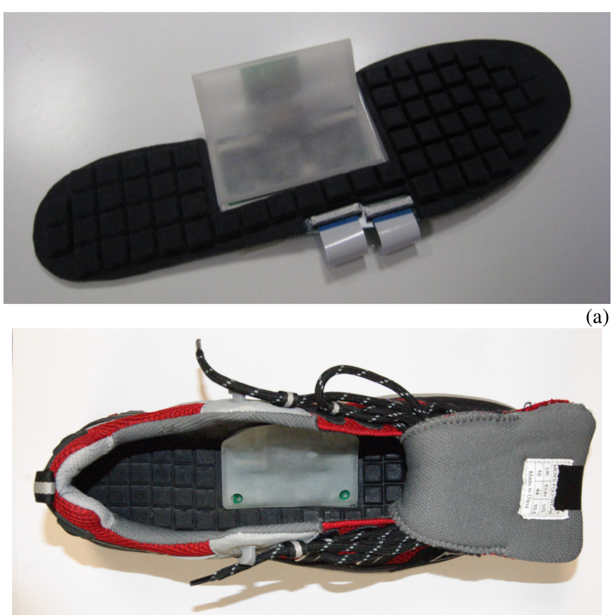
The final appearance of the insole is shown in Figure 7(a) and (b). As a preliminary validation of the device, we performed a walking experiment on a healthy subject wearing the insole inside a sport shoe. Data relative to 5 steps were recorded. Figure 8 shows the center of pressure position profile during the stance phases of the 5 steps.

V. Conclusion

We developed a new in-shoe device to monitor plantar pressure consisting in a matrix of 64 pressure-sensitive elements, integrated with in-shoe conditioning electronics and battery. The device can replace the insole of commercially available shoes, without interfering with the normal gait, and allowing the user to wear his/her own shoe.

The device allows to monitor shoe-foot interaction with a high temporal (100Hz) and spatial ($1cm^2$) resolution, compared to state-of-the-art in-shoe devices. The on-board electronics acquires and digitalizes the signals, computes the pressure map in real-time using proper calibration curves, ,evaluates the center of pressure, and the ground reaction force and finally transmit all these information through Bluetooth. This allows also low-computational-power remote devices (like smartphones) to provide visualization and logging of data from the insole.

These features, along with its long-time autonomy, make the proposed device very useful to monitor the gait and for the assessment of quality of the walk in healthy subjects. Most importantly, this device can used for long-term monitoring of gait (all-day monitoring), thanks to its simplicity of use and to its versatility.



(a)

(b)

Figure 7. Overview of the device. (a) outside of the shoe and (b) inside the shoe.

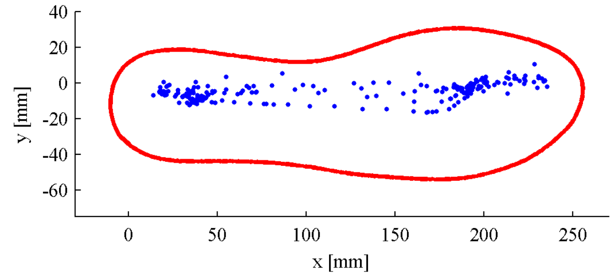


Figure 8. Trajectory of the center of pressures during 5 steps.

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