Autonomous Wearable System for Vital Signs Measurement With Energy-Harvesting Module

Alessandro Dionisi, Daniele Marioli, *Fellow, IEEE*, Emilio Sardini, *Member, IEEE*, and Mauro Serpelloni, *Member, IEEE*

***Abstract*— The growing demand for wearable devices is imposed by the ability to monitor in real-time critical situations in the different areas of daily life. In many cases, power is the limiting factor for such devices. One aspect is the power supply with batteries that introduces issues due to the weight, the overall dimensions, and the disposal of the batteries. A viable solution to overcome the limitations of batteries as power source is to harvest ambient energy to power the devices directly. In this paper, a proposed wearable device with an energy-harvesting module has been designed, manufactured, and tested for the measurement of vital signs. The energy-harvesting module is implemented to directly power the electronic circuit board by a flexible solar panel. This paper describes the proposed instrumented autonomous T-shirt powered by the flexible solar panel applied directly on the T-shirt. The instrumented T-shirt is capable of measuring respiration rate, heart rate, and movement of the body. The methodology adopted, the design choices, and the experimental results are clearly reported and discussed. The experimental results show the functioning even with poor outdoor lighting conditions and under specific indoor constraints. Tests have been conducted aiming to compare the instrumented T-shirt's output data with the data obtained via instruments as gold standards and to show that the overall system described in this paper is capable of producing reliable data compared with the data obtained with these instruments.**

***Index Terms*— Autonomous system, heart rate monitoring, instrumented T-shirt, power harvesting, respiratory frequency monitoring, solar cell, vital sign monitoring, wearable system.**

I. Introduction

A WEARABLE system can be a viable solution for monitoring the principal vital signs of a person during daily activities for a variety of applications in the medical, sport, and wellness fields. In the medical field, one of the most compelling problems is the care to the elderly population that is expected to grow in the next years, since it raises questions about the cost of the structures and assistance activities. In particular, the availability of devices capable of autonomously monitoring elderly subjects during daily life measuring the body's primary functions guarantees the first assistance and provides a primary response to the emergencies. Monitoring devices that are able to check the physiological status make it possible to assist the elderly person in his/her typical life place also outdoor, for example, street, supermarket, café, or church. The main advantages are decrease in the health costs both for the patient and for the medical corps, of the waiting time and of the overcrowding in the medical structures; on the other hand, the increasing of the people independence and their autonomy improve their quality of life [1], [2]. Other interesting application fields are sports and wellness; in fact, wearable systems can constantly monitor the performance of the athlete and provide information in real time to improve constantly his/her physical activity. Therefore, it is expected that these devices can operate for an extended time where the activity is held, even outdoors.

In the literature, some biomedical wearable systems equipped with sensors and suitable electronics to condition and store the vital signals have been reported. In [3], LifeShirt is a garment made with Lycra fabric and it measures the main biomedical parameters such as electrocardiogram (ECG), frequency of leg movement, temperature, blood oxygen saturation, blood pressure, and respiration activity. Data are recorded in a cellular device and sent to the VivoMetrics Data Center where summary reports are generated to resume the patient status. MAIN Shirt [4] is a wearable device that consists of four noncontact sensors based on electromagnetic coupling between a coil and the thorax due to magnetic eddy current induction to monitor respiration and pulse activities. The sensor is a coil realized by high-frequency litz wire that is sewn into a shirt. MAIN Shirt was also successfully tested for motion pattern recognition in [5]. The same research group developed a wearable device combining magnetic induction and reflectance photoplethysmography for cardiorespiratory monitoring [6]. MagIC [7] is an interactive shirt used for the home monitoring of cardiac patients. The vest integrates ECG electrodes made by conductive fibers, a textile piezoresistive plethysmograph, and a three-axis accelerometer to detect subject's movements. All the signals are sent via Bluetooth to a remote monitoring station. Therefore, a rechargeable lithium-ion battery is necessary to power the system. This device allows more than 60 h of continuous activity per charge but is not classifiable as low power. Biotex is an European Union (EU)-funded project that aimed to develop textile sensors to measure physiological parameters and the chemical composition of body fluids. The team has designed a jacket composed of elastic band that includes a number of textile sensors distributed around the body measuring sweat rate, ECG, respiration, and blood oximetry [8]. Squid is a

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The authors are with the Department of Information Engineering, University of Brescia, Brescia 25123, Italy (e-mail: mauro.serpelloni@unibs.it).

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smart shirt equipped with smartphone application and an online database [9]. This system incorporates electromyography (EMG) sensors, heart rate data acquisition circuit, and audiovisual feedback to the user. The collected data are stored by Bluetooth in an online database for the purpose of personal monitoring and distant therapist's supervision. Another system for long-term continuous monitoring of vital signals is described in [10]. The authors have designed a wearable sensor node that is able to monitor the patient's vital signs and fall detection. The system could not be classified as low power because the current consumption is 150 mA. In [11], a smart shirt that measures the ECG signals and the acceleration for the continuous health monitoring was designed and developed. However, the possibility of measuring the respiratory activity is also crucial to check the patient health. Medical analysis shows that the most important parameters are those that specify the functionality of heart and respiratory system [4]. A particular technique to measure the respiratory activities is presented in [12]. This paper exploits highly flexible polymeric optical fibers, which react to applied pressure due to chest movements. In [13], a wearable system that transmits data to the patient's personal digital assistant via Bluetooth is shown. In [14], a system of wireless real-time monitoring measures three-axis accelerations using an accelerometer, ECG, and temperature. The system has an optimized power consumption of about 16.6 mW and it is powered by a lithium battery. In most of the previous cases, the systems operate in continuous mode powered by rechargeable batteries and often the power consumption is not indicated.

A system interfacing with people who need to be monitored and in particular with elderly people, in the medical field, or with athletes, in the sports field, must have specific requirements to be accepted and used. In many cases, power consumption is a limiting factor for such devices. For example, in assistive applications or outdoor applications, the use of batteries as a power source has several drawbacks such as the battery life, the need to replace periodically or to recharge with fixed energy sources, and their relatively large size and weight. Batteries unfortunately affect both for their weight and for their volume, and they constitute a problem to the environment, since they create problems of replacement and disposal. A viable solution to overcome the limitations of batteries as the power source is to harvest ambient energy to recharge, or better to directly power the devices. Bhatnagar and Owende [15] show that energy harvesting is becoming a feasible way for the supply of a wide range of autonomous systems. Thus, the development of self-powered autonomous systems powered by energy harvesting is an area of research that offers much potential [15]. The main idea is to use an energy source provided by human, such as kinetic and thermal, or present in the environment, such as solar energy or RF radiation, to supply a low-power wearable device. These energy sources have different characteristics, such as maximum power available and power densities [16]; therefore, different energy harvesters have been studied recently. However, up to now few autonomous wearable devices supplied by an energy-harvesting module are reported in the literature. In [17], a thermoelectric generator to supply a wearable device and extend its lifetime is shown. The harvester powers a self-sustaining active wireless sensor node for temperature measurement in the body sensor network. In [18], the thermoelectric module generates power in 5–0.5 mW range at ambient temperatures of 15 °C–27 °C, respectively, but, as in the previous reference, no vital signs, such as heart rate or respiration rate, are measured. In fact, despite the various advantages of thermoelectric modules, their limitations for vital signs monitoring comprise a low efficiency rate in the conversion of energy, the need for a constant heat source, and limited possibilities of application in wearable devices, because the form should be flexible and should adhere strictly to the human body [19]. Recently, triboelectric generators have been developed that can harvest electrical energy from mechanical friction, exhibiting high performance, a simple fabrication process, cost effectiveness, and green technology [19]. In [20], a triboelectric harvester was applied to a power shirt with a wireless temperature sensor and with a 2.2-μF capacitor charged to 2.4 V in around 27 s. However, this time interval could be a problem for cardiorespiratory monitoring. In fact, triboelectric harvesters work only when the wearer is moving as kinetic energy harvesters. An example of wearable device for human activity recognition and supplied by a kinetic energy is reported in [21]; the wearable device has relevant dimensions and it can work just when the person is moving.

As pointed out in [15], the harvesting of solar energy can be an efficient solution for different wearable applications. For example, Brogan *et al.* [22] present the design of a wearable energy-harvesting jacket, which harvests energy from solar and body heat in the outdoor environment, but no vital signs are measured. In [23], a solar powered wrist worn acquisition system for continuous photoplethysmogram (PPG) monitoring is presented. In low-light situations, the device obtains a 5-s PPG waveform every minute consuming an average power of 0.57 mW. In [24], a wearable sensor node is able to continuously monitor the temperature of the wearer, read, and transmit back to the base node in a wireless manner with a flexible solar panel. Therefore, among the energy-harvesting techniques, the solar energy seems the more feasible for a battery-less self-sustained wearable system for vital signs monitoring.

Aiming to demonstrate the proof of concept, an instrumented wearable garment for wireless health monitoring was designed and a first prototype was described in [25]–[27]. First a belt and then a shirt were developed to monitor the principal subject's vital signs. These solutions are not low power; in particular, they use a Bluetooth transmission with a current consumption of 40 mA at 3.3 V sending the data to a remote central unit for the following processing. Therefore, in [28], a low-power electronic board, supplied by battery, has been designed to improve all day long acquisition.

This paper describes a battery-less self-sustained wearable system for heart rate, respiration rate, and torso movement measurement. An energy-harvesting module, which implements a flexible solar panel, is used to supply the electronic circuit board of the wearable system obtaining a novel autonomous system. Consequently, the wearable system

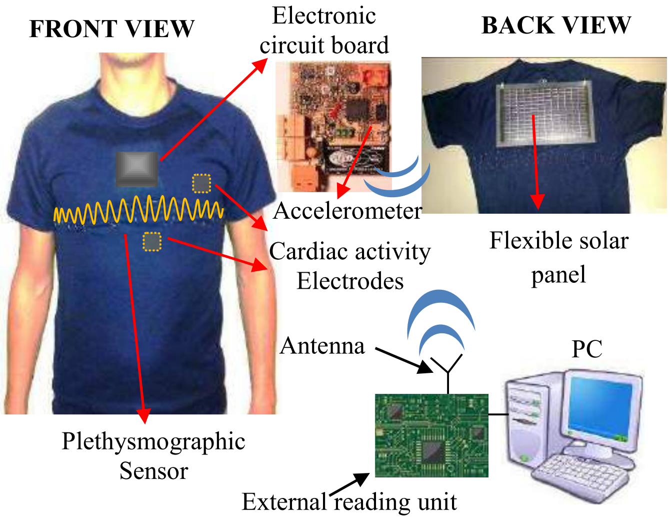

Fig. 1. Overall view of the wearable system with details about the autonomous instrumented T-shirt.

is designed keeping attention to low-power characteristics. The supplying power is decreased by using low-power circuits for heart rate and respiratory rate measurements, and the data transfer is obtained by a low-power RF module. Several tests relating to the evaluation of the overall system behavior when powered by the energy-harvesting module in different lighting conditions, with different orientations and indoor were conducted. The experimental results concerning the functioning of the overall system in different contexts have been reported and commented in the text. Furthermore, other tests have been conducted aiming to compare the instrumented T-shirt's output data with the data obtained via instruments as gold standards and demonstrate that the overall system described in this paper is capable of producing reliable data compared with the data obtained with these instruments. Finally, a critical discussion on the different aspects regarding the feasibility of the overall system is reported.

II. Autonomous Wearable System Architecture

The wearable system with details about the autonomous instrumented T-shirt is schematically shown in Fig. 1.

It can be divided into several blocks:

1) a T-shirt that is made of single jersey cotton with Lycra for enhanced comfort and good body adherence;
2) the electronic circuit board including conditioning sensor circuits, accelerometer to measure body tilts, and wireless transfer module;
3) the textile conductive sensors measuring cardiac and respiratory activities (cardiac activity electrodes and inductive plethysmographic sensor);
4) the flexible solar panel used as energy-harvesting system to supply the circuit board;
5) the external reading unit, which receives the data from the circuit board wirelessly and is directly connected to a personal computer (PC).

Flexible solar panels of the PowerFilm Solar were investigated due to the small dimensions and the flexibility that permits the wearability of the T-shirt. These devices are built by roll-to-roll manufacturing process realizing monolithically integrated solar panels on plastic obtaining a substrate of 0.025 mm, and finished panels are encapsulated in materials appropriate for the application environment. The PT15-150 (PowerFilm WeatherPro Series) solar panel has been chosen as energy-harvesting source, because it is perfect for permanent outdoor applications. The especially rugged construction of these solar panels includes a UV-stabilized surface, extra edge seal for weather protection, and tin-coated copper leads that extend from the module. Coating the leads with a silicon compound can provide a tightly sealed package. Furthermore, the manufacturer specifications indicate that these solar panels are washable. The PT15-150 solar panel has dimensions of 270 mm × 175 mm and 56.4 g of weight and can produce 19 V and 100 mA in open circuit and short circuit, respectively. This flexible solar panel is connected to a power management circuit to scale the voltage in input to the supply value of 3.3 V (Fig. 2). The TPS62102 has been chosen as a step-down buck converter because it is low power and has high efficiency. This device has a wide input range of 2.5–9 V, but the solar panel can generate up to 19 V with full sun, and therefore, an 8.2 V Zener diode has been added in the input to the step-down converter to limit the input voltage. A storage capacitor (supercapacitor) has been connected to store the energy in excess coming from the solar panel. An electric double layer capacitor with a capacity of 1 F, a nominal voltage of 3.6 V, circular dimension with a diameter of 21.5 mm, and a thickness of 9.5 mm has been used. In short eventualities of unfavorable solar conditions, the energy stored in the supercapacitor can be used to supply the electronic board for about 2 min. This power management circuit has a current consumption of about 0.6 mA.

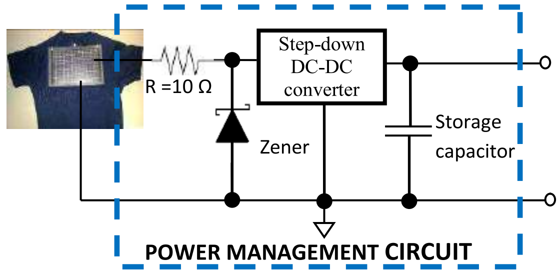

Fig. 2. Block diagram of proposed solar energy-harvesting module.

In Fig. 3, the block diagram of the entire electronic circuit board is shown. This electronic circuit board has been designed with particular attention to power consumption minimizing as much as possible the current absorbed by the various measurement modules. The dimensions are 5.5 cm × 4.5 cm and the weight is 25 g. In this configuration, the electronic circuit board was realized double sided using printed circuit board (PCB) technique, but it can be easily manufactured with flexible PCB technique as well. This electronic board is placed in a pocket at the center of the chest and fixed and connected through snap buttons. The electronic circuit board is connected to two electrodes for the measurement of the cardiac activity, to the plethysmographic sensor for the measurement of the respiration activity, and to the flexible solar panel. The low-power 8-b MC9S08QE128, which has a current consumption

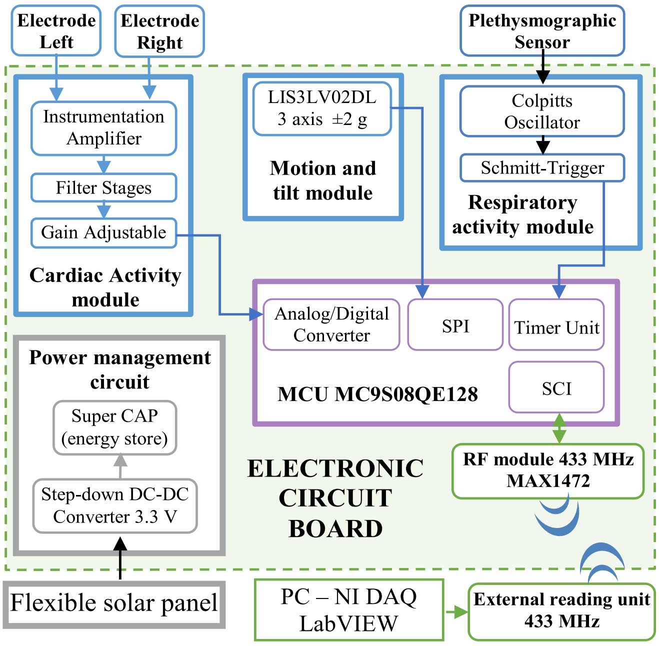

Fig. 3. Architecture of the wearable system.

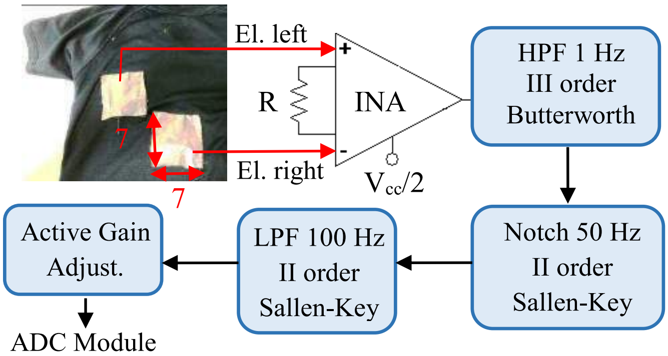

Fig. 4. Electronic circuit for the conditioning of the cardiac signal generated from two textile electrodes in left- and right-center position (the inside of the T-shirt).

in run mode of about 4 mA and in sleep mode of about 0.5 mA, manages the sensor signals acquisition and data transmission. The electrodes measuring the cardiac activity are connected to a front-end electronics, and then the output signal is converted by 10-bit analog-digital converter (ADC) converter inboard to the microcontroller. The plethysmographic sensor is connected to a specific conditioning circuit described later, and then the signal is acquired by the microcontroller using its timer unit. Finally, the data generated from the digital triaxial accelerometer are acquired by the microcontroller using the Serial Peripheral Interface (SPI) interface. The measurement algorithm of the microcontroller is programmed to sample, convert, and send the data with a frequency of 100 Hz. This frequency has been selected with the aim of obtaining useful signals also when the heart rate and the respiratory rate are very high. Furthermore, the stop mode is used in the algorithm to reduce the power consumption after the data transmission. The real-time interrupt wakes-up the microcontroller and starts another measurement cycle each 10 ms. The microcontroller sends the stored data to the external reading unit using an RF module, a low-power RF transmitter (MAX1472, Texas Instruments), which has a current consumption in transmission of about 4 mA and about 300 nA in sleep mode. The frequency range for this type of transmitter is 433 MHz and the modulation mode is amplitude shift keying (ASK) with 90 dB of modulation depth that guarantees some meters of transmission distance. The antenna is ANT-433-SP (Linx Technologies), which has an ultracompact package and very low cost. The data sent by the MAX1472 are received by the module 4312-DKEB1 marketed by Silicon Laboratories. The output signal from the 4312-DKEB1 cannot be directly acquired by the PC, but it is necessary to use an intermediate unit. In this research project, a data acquisition board marketed by National Instrument was used for this purpose. Therefore, a dedicated program has been developed in LabVIEW. This program processes the received vital signs data and saves and shows the physical status information to a video interface.

A. Cardiac Activity Module

The measurement of the cardiac activity is made using two textile electrodes sewn directly on the T-shirt, as shown in Fig. 4. The advantage of textile electrodes [29] with respect to the classical dry electrodes, contact [30] and noncontact [31], is that they are made of ordinary fabric, soft, and flexible and they do not cause skin irritation; therefore, they are appropriate for chronic long-time applications.

The two electrodes are located inside the T-shirt on the right center and the left chest, which guarantees a maximal expression of the R complex and allows calculating the heart rate using the distance between the peaks of the signal.

The electrodes are realized using a conductive metallized nylon fabric (Nora Dell) commercialized by Shieldex, with dimensions of 7 cm × 7 cm. This material is a lightweight rip-stop fabric woven with nylon monofilament that has been plated first with silver, then with copper, and finally with nickel to provide weatherability and protect against galvanic corrosion. The textile is conductive having a surface resistance <0.009 Ω/sq. According to the manufacturer specifications, this fabric material has high strength and resistance to the normal conditions of use such as multiple deformations for wearable application. Furthermore, the conducting fabric can be washed due to the ability to resist temperature up to 150 °C [32].

In order to improve the cardiac signal quality, a conditioning circuit has been implemented (Fig. 4). An instrumentation amplifier (INA), the low-power INA333 (Texas Instruments), performs the difference between the signals coming from the two electrodes. This INA has a high Common Mode Rejection Ration (CMRR), 100 dB, and extremely high input impedance, approximately 100 GΩ. Then, a third-order Butterworth high-pass filter, a selective second-order filter at 50 Hz and a second-order low-pass filter in Sallen-Key configuration are implemented. Adopted passive components have tolerance less than 1% and very low temperature coefficients. As reported in Fig. 3, using a single supply of 3.3 V, it is been necessary to shift the signals of $V_{cc}/2$ by means of the 1.8 V voltage reference. The cardiac signal conditioning circuit has a current consumption of about 0.2 mA.

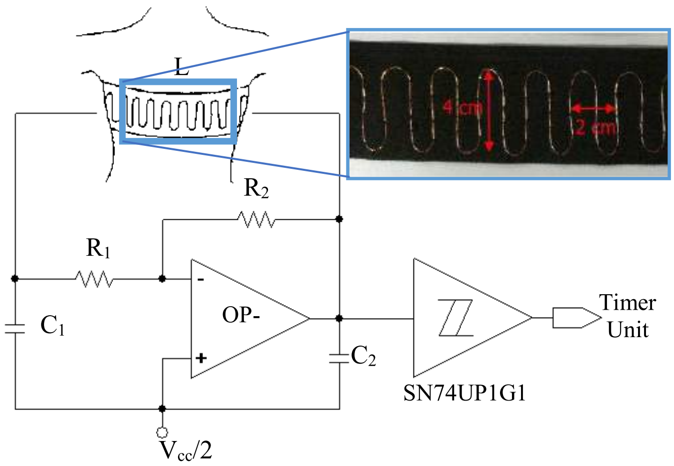

Fig. 5. Electronic circuit for the breathing rhythm measurement that exploits the inductance change in an oscillator circuit and plethysmographic sensor that measures the thorax volume change by the inductive effect created from the copper coil.

B. Respiration Activity Module

The respiratory rate measurement technique is based on the inductance variation of an inductive sensors due to dimension coil change when it is applied a stretch generated by the rib cage movements during inhaling and expiration. The sensor consists of a wire of copper sewn to the T-shirt with a sinusoidal form of height of 4 cm and step of 2 cm. The inhaling value is lower than the expiration value, because during inhaling, the chest volume increases and the coil is stretched out. In this case, the magnetic field included between the coils is higher and therefore the inductance increases. To perform the measurement, the inductive sensor is used in a Colpitts oscillator circuit feedback, as in Fig. 5. The setup of the measurement circuitry including the Colpitts oscillator is a feasible solution for noncontact measurement [33] and it permits low-power consumption.

The Colpitts oscillator consists of a parallel LC resonator tank circuit whose feedback is achieved by a capacitive divider. This configuration uses a capacitor voltage divider as its feedback source. The Colpitts oscillator works around the 400-kHz frequency, where the sensor has a mainly inductive behavior, with a span of about 5 kHz. The two capacitors C_1 and C_2 are placed across a common inductor (the sewed sensor) L as shown so these components forms the tuned tank circuit. The designed Colpitts oscillator uses a single operational amplifier as the gain element that produces a sinusoidal output. The frequency of oscillations for this circuit is determined by the resonant frequency of the LC tank circuit and it is given by

$$f_r = \frac{1}{2\pi\sqrt{LC_T}} \tag{1}$$

where C_T is the capacitance of C_1 and C_2 connected in series. Resistors R_1 and R_2 provide the gain of the circuit. In this way, the oscillation frequency changes with the inductance variation due to the chest volume, which increases or decreases during the respiratory activity. The oscillator output signal is squared through a low-power integrated Schmitt trigger (SN74AUP1G17) in order to make readable the modulated signal to a 16-b timer unit of the microcontroller. In the proposed solution, two 16-b timer units integrated in the microcontroller are activated. One detects high edges in capture mode and the second timer unit is used as a counter with a fixed update frequency of 2 MHz (the bus clock is 4 MHz) measuring the time interval between two consecutive edges. When new high edge is been detected, the timer subtracts this new time value with the previous to obtain the period and the signal frequency consequently. The respiration conditioning circuit has a current consumption of about 0.8 mA.

C. Motion and Tilt Module

The measurements of the positions and the main tilts of the chest are made by an accelerometer of the STMicroelectronics, the low-power LIS3LV02DL. It is a triaxial digital output linear accelerometer composed by an inertial system and an integrated circuit interface to provide the measured acceleration signals through an SPI interface. The human body motion frequency typically belongs to the range 0.5–10 Hz in accordance with the locomotion studies. For example, measured frequencies for chest, back, and shoulder are included in the range 1.7–2 Hz [34], whereas the walking gait cycle frequency is about 1.0 Hz [35]. The digital triaxial accelerometer can be used to tilt-sensing applications due to its capacity to measure static acceleration assuming that the gravity acceleration is the only acceleration value acted on the human body. Other accelerations, such as the dynamic contribution and the artifact due to the fabric movements, where the electronic board is fixed, are filtered by a low-pass filter with a cutoff frequency of 0.5 Hz, according to [36]. In our application, a measurement range full scale of ± 2 g and an output data rate of 160 Hz are used. With this configuration the accelerometer resolution is 1.0 mg and the sensitivity is 1024 LSBs/g, about 1 mg. Two rotation angles of the body are measured:

1) the anteroposterior angle, which represents the body tilt in the frontal plane;
2) the mediolateral angle, which indicates the movements in the sagittal plane.

These angles are calculated by means of the three acceleration values using the inertial measurement unit theory [25].

III. Experimental Results

Measurements have been carried out to check the power consumption in terms of current.

In Fig. 6, the current consumption profile of the overall system obtained using an oscilloscope measuring the voltage drops across a 10-Ω resistor (R in Fig. 2) in series with the solar panel is shown. The reading data and the send data trends are shown superimposed to the current consumption profile. In particular, the current trend shows four steps between run mode and sleep mode (Fig. 6): reactivation phase, reading phase, transmission phase, and sleep mode. These measurements indicate that the mean power consumption is about 17 mW including run and sleep phases.

A preliminary study was performed to evaluate the behavior of the designed system and to demonstrate the self-sustainability and flexibility of the T-shirt directly connected

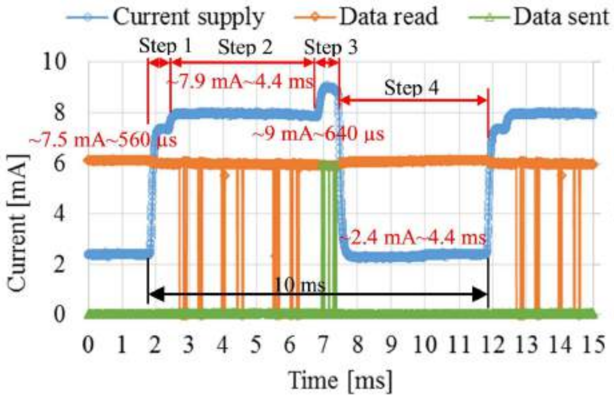

Fig. 6. Current consumption trend compared with the data read and the data sent.

TABLE I
DESCRIPTION OF THE TEST CONDITIONS

Place	Case	Weather, time, daydate	Measurement Description
Outdoor	1	Sunny 10:30–17 Dec. 10	Sunny area Panels stationary in (N), (S), (E), and (W) Panels positioned vertically (90 deg.)
	2	Sunny 10:30–17 Dec. 10	Sunny area Panels stationary in (N), (S), (E), and (W) Panels positioned at 45 deg.
	3	Sunny 10:30–17 Dec. 10	Sunny area Panels stationary in (N), (S), (E), and (W) Panels positioned horizontally (0 deg.)
	4	Cloudy 10:30–17 Dec. 11	Shadow area Panels stationary in (N), (S), (E), and (W) Panels positioned vertically (90 deg.)
	5	Cloudy 10:30–17 Dec. 11	Shadow area Panels stationary in (N), (S), (E), and (W) Panels positioned at 45 deg.
	6	Cloudy 10:30–17 Dec. 11	Shadow area Panels stationary in (N), (S), (E), and (W) Panels positioned horizontally (0 deg.)
Indoor	7	Sunny 10:30–17 Dec. 12	Window exposed to North Panels stationary to North Panels positioned vertically (90 deg.)
	8	Sunny 10:30–17 Dec. 12	Window exposed to South Panels stationary to South Panels positioned vertically (90 deg.)

to the energy-harvesting module in outdoor environments. The tests were carried out in different days of mid-December, which can be considered the worst case in the whole year in Europe for light conditions. Tests were conducted with the proposed system powered by the energy-harvesting module in various environments both outdoor in different lighting conditions with different orientations and indoor, as reported in [37]. In particular, the instrumented T-shirt was worn by a male subject asking to stand for a few minutes in different geographical orientations and with different tilts under full sunlight conditions and in shadow areas. In Table I, the descriptions of the eight test conditions (labeled Cases 1–8) are reported. In the cases from 1 to 6, the overall system was tested in each direction, North (N), South (S), East (E), and West (W) individually. Therefore, each outdoor case has four subcases.

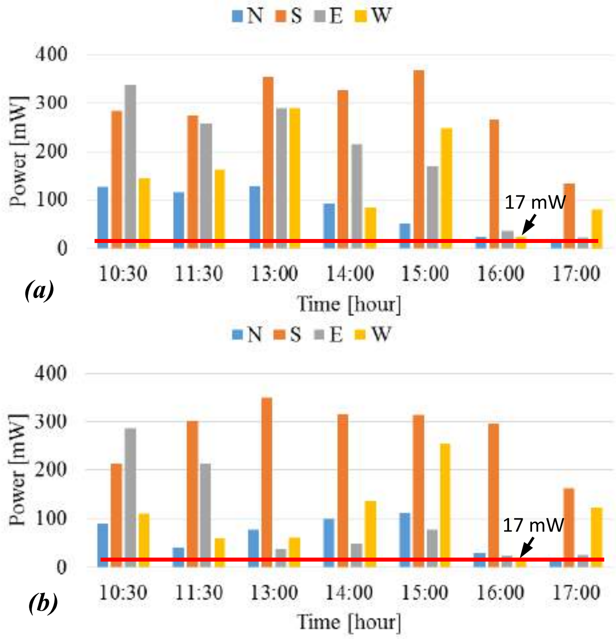

Fig. 7. Experimental results of Cases 1 and 2 in sunny conditions with different tilts of the panel with respect to the horizontal plane. (a) 90°. (b) 45°.

In the following, Figs. 7–12 show the experimental results obtained in the test conditions described in Table I. Figs. 7–12 show the power values calculated measuring the average currents on the resistor of Fig. 5 and the average voltage across the solar panel and checking the functioning of the overall system.

Fig. 7(a) and (b) shows the experimental results of Cases 1 and 2. The person wearing the T-shirt has been positioned in the four cardinal directions, North (N), South (S), East (E), and West (W) and with two tilt angles 90° and 45°. The generated power, when the panel is facing south, is higher than the other conditions because in the north of Italy the sun is in the south. Thus, the sunlight was directly hitting to the flexible solar panel. The measurements have been repeated during the whole day in different hours. With a red line, the power limit of the overall system operation is highlighted. Therefore, the power generated from the solar panel is sufficient to supply the electronic circuit board during the measurement operations when the person is outdoor under the sun in all the conditions reported in Cases 1 and 2.

In Case 3, the tests were carried out when the person is prone forward and the flexible solar panel fixed on the back is parallel with respect to the horizontal plane. Fig. 8 shows the experimental results of Case 3. The sunlight hit in all directions on the solar panel and the generated power is sufficient to supply the wearable device during all the day.

In Cases 4–6, the tests were carried out on a sunny day but in shady areas to verify the behavior of the overall system in poor light conditions. As before, the measurements were acquired for different cardinal positions and different tilt angles of the panel with respect to the horizontal

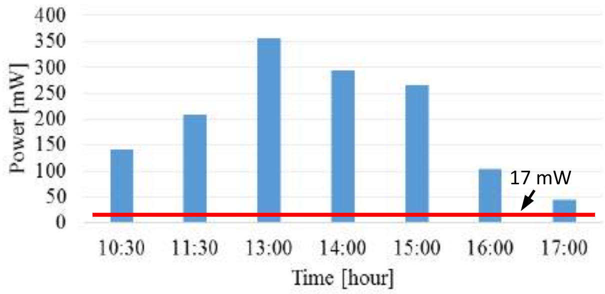

Fig. 8. Experimental results of Case 3 in sunny conditions when the person is prone forward and the panel is parallel to the horizontal plane (0°).

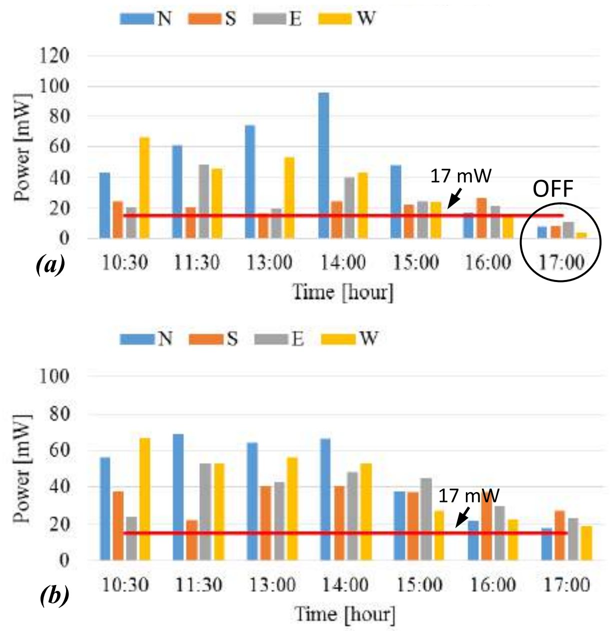

Fig. 9. Experimental results of Cases 4 and 5 in shadow areas with different tilts of the panel with respect to the horizontal plane. (a) 90°. (b) 45°.

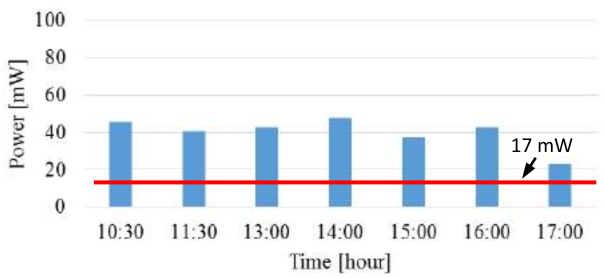

Fig. 10. Experimental results of Case 6 in shadow areas when the person is prone forward and the panel is parallel to the horizontal plane (0°).

plane. Fig. 9(a) and (b) shows the experimental results of Cases 4 and 5. In more of the subcases, the power was sufficient to supply the overall system. Only in the late afternoon of Fig. 9(a), the power was less than that required in all positions and directions.

In Case 6, the tests were carried out when the person was prone forward and the flexible solar panel fixed on the back was parallel with respect to the horizontal plane. Fig. 10 shows the obtained experimental results. The sunlight

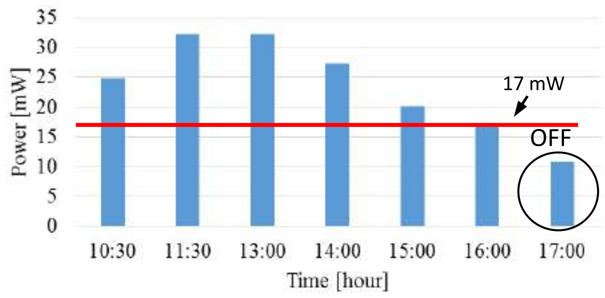

Fig. 11. Experimental results of Case 7 when the subject is positioned with the back in front of a window exposed to north.

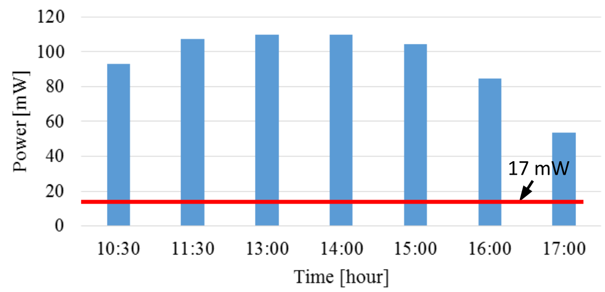

Fig. 12. Experimental results of Case 8 when the person is positioned with the back in front of a window exposed to south.

did not hit on the solar panel, but it was reflected. However, the generated power was sufficient to supply the wearable device during all the day. The experimental results confirm the self-sustainability of the overall system during all the day, also in shady areas.

The overall system has also been tested indoors. The subject wearing the smart T-shirt was positioned with the back, where is located the flexible solar panel, in front of a window at a distance of about 1 m. We have experienced that, if the person is with the back not in front of the windows, the system is off. As described in Table I for Cases 7 and 8, two different measurements were conducted, the subject's back was facing two windows one exposed to the north and another to the south. Figs. 11 and 12 show the obtained experimental results. The generated power is less than the outdoor cases, but it is sufficient to supply the overall system. Only in late afternoon and with the person exposed with back to the north, the smart T-shirt did not work. The two cases, although limited to particular conditions, demonstrate the feasibility even indoors under special conditions and they can be the starting point for research aimed at extending the possibility of use even in a closed environment.

In the outdoor tests in sunny areas and shady areas, the illuminance value was monitored by a light sensor embedded on a smartphone. The observed threshold value to power on the electronic circuit board is about 1500 lx. This value gives an indication for compatible working condition that corresponds to the standard illuminance provided in overcast days [38].

Different tests were performed to assess the behavior of the proposed instrumented T-shirt for vital signs measurement. Experimental measurements about the cardiac activity measurement are shown in Fig. 13. In particular, the acquired

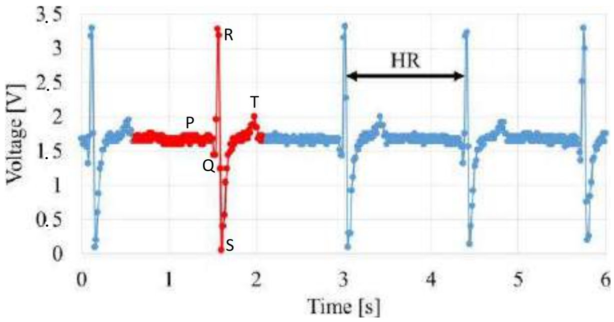

Fig. 13. Cardiac signal recorded during resting activity. The red line highlights a PQRST complex. The subject monitored has a heart rate of about 42 b/min.

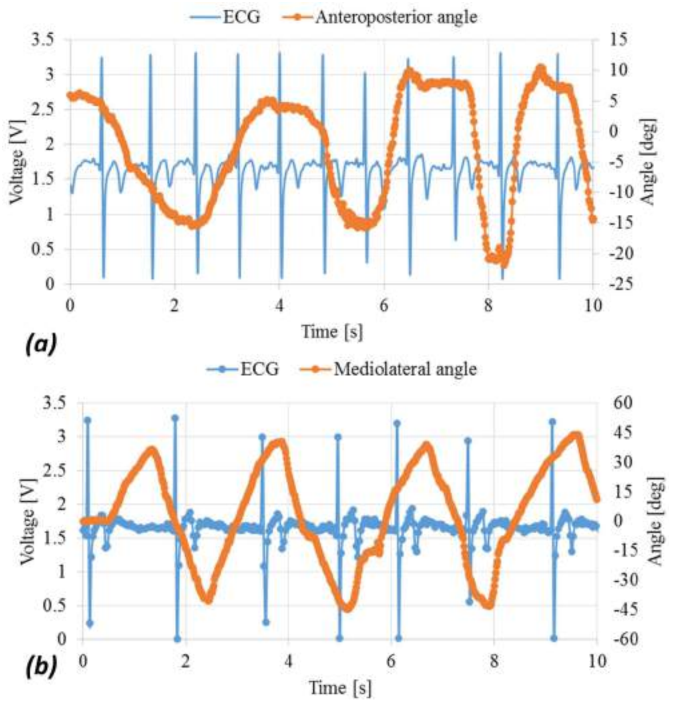

Fig. 14. Comparison between the cardiac signals with (a) anteroposterior angle of the patient in stand-up or sit-down activities and (b) mediolateral angle when the patient oscillates in the right and left directions.

cardiac signal shows the curve PQRST; according to the lead II mode, the P wave during normal atrial depolarization is not visible, whereas the T wave representing the repolarization of the ventricles is more accentuated. The information relating to the heart rate can be calculated measuring the time between consecutive picks due to the QRS complex that represents the rapid depolarization of the right and left ventricles. In addition, the QRS complex measured reflects the typical layout of the lead II configuration where the QRS has a large amplitude because the ventricles have a large muscle mass compared with the atria.

In Fig. 14(a), the cardiac signal when a person stands-up and sits-down from/on a chair continuously is shown. The measured signal is superimposed with the anteroposterior angle measured by the triaxial accelerometer, whereas Fig. 9(b) superimposes the cardiac signal with the mediolateral angle when the patient oscillates right and left. These graphs

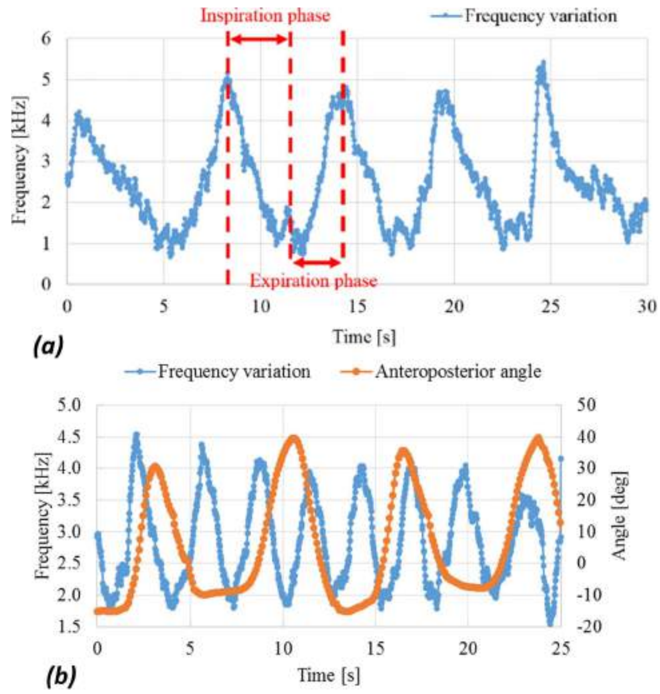

Fig. 15. (a) Frequency change of the oscillator circuit produced by the respiration during resting activity. The subject monitored had a respiration rate of about 10 breaths/min. (b) Comparison between the respiration signal with the anteroposterior angle of the patient in stand-up or sit-down activities.

indicate that the cardiac signal is less affected by the noise due to the movement of the person.

In Fig. 15(a), the output signal of the respiratory circuit is shown. The signal represents the relative frequency change of the output signal produced by Colpitts oscillator. Using the timer unit of the microcontroller in input capture mode was measured the real-time frequency of the Colpitts oscillator and consequently the respiratory rate. The oscillator circuit generates an output signal with frequency of inhalation less than exhalation because the inductance increase in according to growth the chest volume. An about 5 kHz of change frequency is measured between exhalation and inhalation phase. In Fig. 15(b), the respiration signal when a person stands-up and sits-down from/on a chair continuously is shown. The measured signal is superimposed with the anteroposterior angle measured by the triaxial accelerometer. This graph indicates the cardiac signal is less affected by the noise due to the movement of the person.

Furthermore, the tests were conducted aiming to compare the instrumented T-shirt's output data with the data obtained via instruments as gold standards and to show that the overall system described in this paper is capable of producing reliable data compared with the data obtained with these instruments. These tests were obtained with the energy-harvesting module connected to the circuit board. No other power sources where used. An instrument for cardiopulmonary measurement in the open environment, usually adopted as reference in the literature (Cosmed k4b2) was used, whereas for the body tilts, the experimental results have been compared by those obtained by an optical measurement system typically used in experiments for gait analysis (Codamotion).

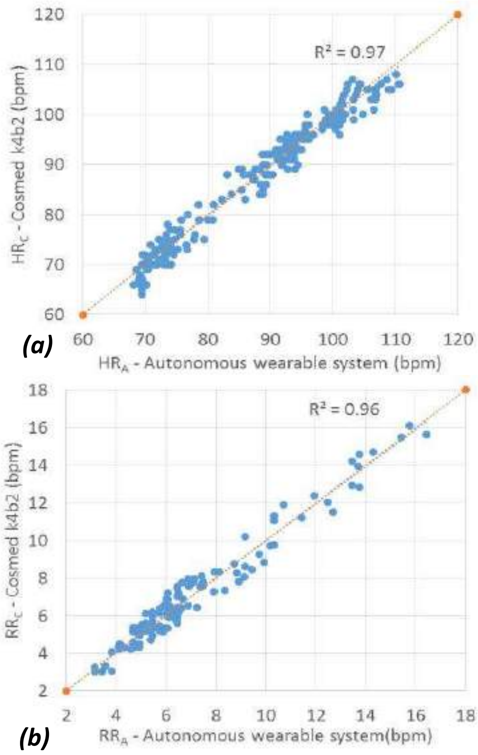

Fig. 16. Plots of the comparison between (a) heart rate in beats per minute obtained from the autonomous wearable system (HR_A) and from the Cosmed k4b2 (HR_C) and (b) respiratory rate in breath per minute obtained from the autonomous wearable system (RR_A) and the Cosmed k4b2 (RR_C). The identity line and the least-squares fitting index (R^2) are shown.

The tests were carried out outdoors on a healthy male subject using the autonomous wearable system and the Cosmed k4b2 at the same time. The synchronization is assured triggering the acquisition starting point and measuring the acquisition time for each sample for both systems. The subject was asked to stand for a few seconds, and then to walk increasing the velocity and to repeat these activities for a few minutes. These tests were performed in collaboration with physiatrists at Riabilitazione Neuromuscolare e Biomeccanica delle Attività Motorie Adattate (LARIN) in Casa di Cura Domus Salutis (Italy).

Fig. 16 shows a comparison between the two systems. The values are calculated considering two-beat and three-beat average for Respiration Rate (RR) and Heart Rate (HR), respectively, over the entire recording length. A similar approach is proposed in [39] and [40]. The index R^2 that represents the variance of the data with respect to the fitted trend line is about 96%–97% for each comparison. Heart rates (HR_A) and respiration rates (RR_A) obtained by the autonomous wearable system agreed with the rates (HR_C and RR_C) derived by the adopted reference instrument; the absolute mean percent differences are <2% and <5% for heart rates and respiration rates, respectively.

Fig. 17 shows Bland–Altman plots relative to heart rate and respiration rate data of Fig. 16. We can observe negligible bias [0.38 b/min, Fig. 17(a), and 0.02 b/min, Fig. 17(b)] and no proportional errors in heart rate and respiration rate assessed by the two methods. Therefore, the autonomous wearable

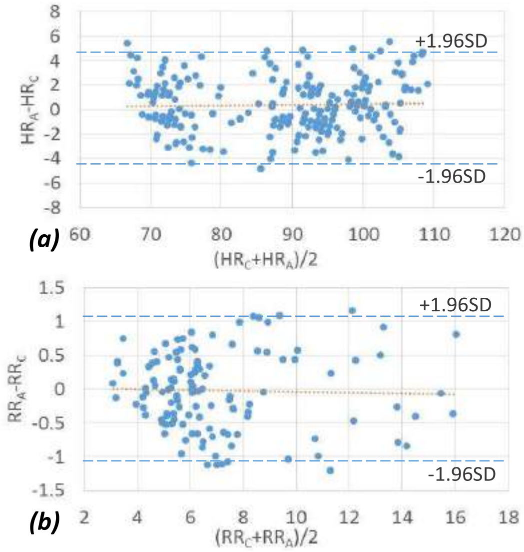

Fig. 17. Bland–Altman plots relative to (a) heart rate and (b) respiration rate obtained from the autonomous wearable system (HR_A and RR_A) and the Cosmed k4b2 (HR_C and RR_C). Dotted line: linear regression line.

system is capable of producing reliable data compared with the data obtained with Cosmed k4b2.

To evaluate the accelerometer data it has been used a 3-D Motion Capture commercialized by Codamotion. The 3-D motion capture is able to measure, analyze, and report on 3-D human movements in a variety of different applications even outdoor. The system is composed by three cameras to acquire the spatial coordinates due to the active infrared marker located on the body of the person. Exploiting the marker coordinates, the angular inclination of the imaginary axes with respect to the horizontal plane can be calculated. In this way, it is possible to calculate the anteroposterior and mediolateral angles using the Codamotion data in order to compare it with the accelerometer data.

Three different tests were executed aiming to evaluate the wearable system behavior during typical day-life activities and high-risk situations: 1) fall-ahead; 2) fall-back; and 3) lateral imbalance. The event that represents the fall-ahead of a person is recognizable by the anteroposterior angle because the person flexes his body in forward and arrives to the horizontal position (prone) in correspondence of the +90°, as shown in Fig. 18(a). The person starts to vertical rest position, falls ahead ending in lying flat (+90°), and then recoveries up to vertical position (about 0°). The angle spikes, calculated using the accelerometer, are due to the T-shirt movements close to the electronic board. The chest movement goes ahead so that the board weight pulls the T-shirt, and thus some unwanted dynamic acceleration contributions are generated. In Fig. 18(a), the absolute difference is shown and the average percentage absolute difference is about 1.5° (red line).

In Fig. 18(b), the trends of the anteroposterior angle measured by the autonomous wearable system when the person falls back are shown. As the results obtained in the forward fall, a backward fall of the person is recognizable by the anteroposterior angle especially. In particular, this behavior is inversed with respect to the previous results. In fact, the person starts in vertical rest position, as before, but falls

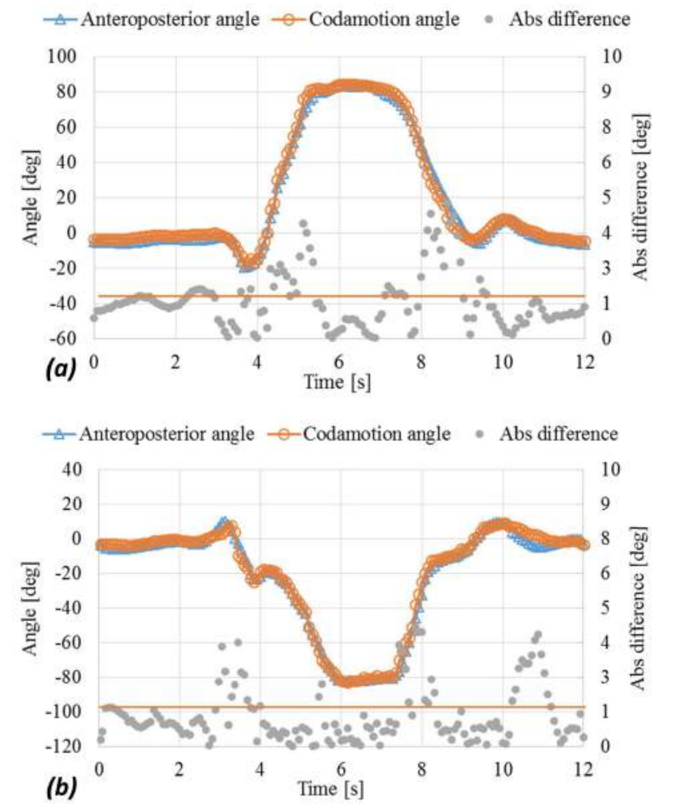

Fig. 18. Anteroposterior angle (a) when the patient falls forward and (b) when the patient falls back starting from the vertical position. Red line: average absolute differences shown in each situation.

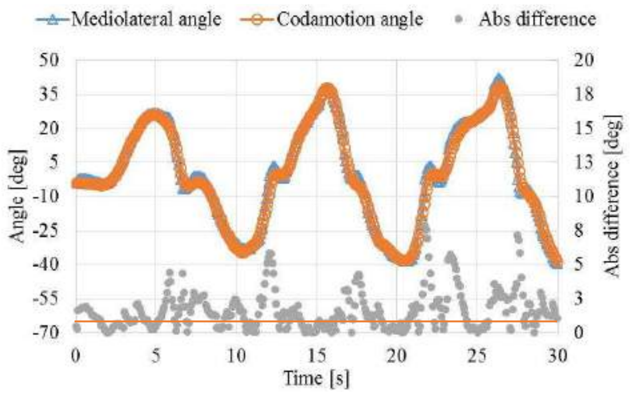

Fig. 19. Mediolateral angle compared with the angle calculated by the Codamotion data when the patient oscillates between the right and left sides, and absolute difference for each acquired sample with the red line that represents the average absolute difference.

back ending in the lying position (supine) assuming $-90°$ as anteroposterior angle value and then recoveries up to the rest position indicated with about 0°. In Fig. 18(b), the absolute difference is shown and the average absolute difference is about 1.5° (red line), similar to the average absolute difference obtained in the fall-ahead exercise.

In Fig. 19, the oscillations on the right and left sides are visible due to the mediolateral angle. When the person is right imbalanced, the mediolateral angle is positive, whereas if the person is left imbalanced the angle is negative. This information is important to know because a person can fall along the left side or the right side. In Fig. 19, the absolute difference is shown and the average absolute difference is about 1.6° (red line).

Therefore, from the experimental results, it is possible to observe that situations of risk can be monitored and it is possible associate alarm states to the surpassing of predetermined thresholds. In this phase, only tests regarding risk events such as falls have been taken into consideration and reported. However, with the accelerometer mounted on the system, other activities as shown in [27] can also be monitored. Furthermore, other aspects such as sweat problems and washability were considered; during the test, the subject did not sweat; however, even if this should happen, the sweat in normal conditions is not supposed to interfere. In fact, the variations in the conductive paths of the currents caused by the sweat are avoided because the conduction wire is enameled, preserving from the possible environment influence and avoiding the contact with the human body. However, we will investigate the use of the proposed T-shirt in different contexts on different physical activities. The instrumented T-shirt with the conductive textile electrodes and wires is washable; the electronic circuit board can be separated from the T-shirt by means of snap buttons and the solar energy panel is waterproof. Finally, an assessment of the invasiveness of the instrumented T-shirt was proposed to the subject wearing it. The subject stated to feel a classic stretch T-shirt. The heart rate electrodes and the respiratory rate sensor are not perceived as outsiders or invasive. The solar panel, although of low weight and small size, is perceived but does not constitute a hindrance to movements. In this regard, the use of more flexible solar panels of smaller size and connected in a suitable manner could also increase even more the subject's acceptability.

IV. Conclusion

In this paper, a novel autonomous instrumented T-shirt powered by an energy-harvesting module is presented; no batteries or other power sources are used. Low-power circuits have been implemented in the circuit board measuring heart rate, respiratory rate, and torso movements. The mean power consumption is very low, about 17 mW, permitting to continuously supply the circuit board by the energy-harvesting module that uses a flexible solar panel to generate the requested power. The instrumented T-shirt has been designed, built, and tested, and thus, the description of each block and the adopted methodological choices have been reported. The experimental results show the possibility of use the T-shirt outdoors in sunny and shadow areas and then in two indoor cases, but with specific constraints. These last two cases, although limited to particular conditions, can be the starting point for an adoption even indoors. Furthermore, the tests were conducted comparing the instrumented T-shirt's output data with the data obtained via instruments as gold standards. The experimental results show that the overall system described in this paper is capable of producing reliable data compared with the data obtained with these instruments.

A further research will investigate a clinical characterization of the vital sign measurements with different subjects. The wearable system with the energy-harvesting module allows improving the noninvasiveness opening up new prospects to develop self-sustained electronic devices for outdoor long-monitoring or with specific indoor constraints, whose applications can be currently limited by the problems associated with the use of batteries. In this regard, the power management could be adapted so as to accumulate a large amount of energy when possible, for example, outside in the sun, in order to use this energy in environments where radiation levels are not sufficient to directly switch ON the system.

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Alessandro Dionisi received the Laurea (Hons.) degree in electronics engineering for automation from the University of Brescia, Brescia, Italy, in 2011, and the Ph.D. degree in technology for health from the Department of Information, University of Brescia, in 2015. His Ph.D. thesis was entitled Autonomous Wearable System for Vital Signs Measurement with Energy Harvesting Module.

He was a Visiting Researcher with the Institut des Systèmes Intelligents et de Robotique, Paris, France, during the Ph.D. degree. He is currently at the University of Brescia, Brescia Italy. He is involved in the design and the implementation of a new electronic nose based on nanowire sensors. His current research interests include electronic instrumentation, sensors, electronic design, wireless transmissions, and firmware development.

Daniele Marioli (F'04) received the Laurea Degree in electrical engineering from the University of Pavia, Pavia, Italy.

He was the Chief of the Automation Electronics Department and the Head of the School in Electronic Instrumentation, and is currently the Vice Rector of the University of Brescia, Brescia, Italy. He has been practicing research and educational activities with the University of Brescia, where he is currently a Full Professor of Electronics. He is involved in the design, realization, and test of sensors, electronic instrumentation, and signal processing electronic circuits. He has authored or co-authored over 300 scientific papers in international and national journals and conference proceedings and holds 11 patents. His current research interests include micromachined silicon sensors and energy scavengers for low consumption sensors and electronic circuits power supply.

Emilio Sardini (M'99) received the Laurea degree in electronics engineering from the Engineering Faculty, University of Brescia, Brescia, Italy, in 1983.

He has conducted research and teaching activities with the Department of Electronics for Automation, University of Brescia, since 1984, where he has been a Full Professor of Electrical and Electronic Measurement since 2006. He has been a member of Integrated Academic Senate and the Board of Directors of the University of Brescia, and the Deputy Dean of the Engineering Faculty. He is currently the Coordinator of the Technology for Health Ph.D. Program, a member of the College of Mechatronics with the University of Bergamo, Bergamo, Italy, and the Director of the Department of Information Engineering. He has done intensive research in the fields of electronic instrumentation, sensors, and signal conditioning electronics. He has authored or co-authored over 100 papers in international journals or proceedings of international conferences. His current research interests include the development of autonomous sensors for biomedical applications, in particular, toward devices implantable inside the human body.

Mauro Serpelloni (M'12) received the Laurea (*summa cum laude*) degree in industrial management engineering and the Research Doctorate degree in electronic instrumentation from the University of Brescia, Brescia, Italy, in 2003 and 2007, respectively.

He has been involved in several projects relating to the design, modeling, and fabrication of measurement systems for industrial applications. He is currently an Assistant Professor of Electrical and Electronic Measurements with the Department of Information Engineering, University of Brescia. His current research interests include biomechatronic systems, contactless transmissions between sensors and electronics, contactless activation for resonant sensors, and signal processing for microelectromechanical systems.