

Review Article

Analysis of the Possibility of Using Energy Harvesters to Power Wearable Electronics in Clothing

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Received 30 December 2018; Accepted 17 March 2019; Published 8 April 2019

Academic Editor: Tomasz Trzepieciński

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The purpose of this study is to analyze the state-of-art knowledge of the use of energy harvesters (EHs) to power the wearables of clothing. The study discusses some examples of clothing with incorporated different types of EHs, harvesting energy from body movement (based on piezoelectric, electromagnetic, and electrostatic phenomena) from temperature differences, as well as from solar radiation. In the performed analysis, particular attention was focused on the design of EHs, their principle of operation, advantages, disadvantages, and restrictions on use. Low energy requirements of wearable electronics (e.g., sensors and diodes) implemented to clothing indicate the possibility of using miniaturized EHs as a power source for such elements. Each of the discussed EH has both disadvantages and advantages. Therefore, the selection of EH should be preceded by a detailed analysis of the conditions of the garment use, its destination, the user's physical activity, and the energy needs of the electronic devices incorporated in clothing. Despite a variety of research studies aimed at developing new EH, relatively few of them concern their implementation in the structure of clothing and tests of their functionality in the foreseeable conditions of use. In view of the above, these issues have been addressed in this publication based on the available literature.

1. Introduction

In the recent years, at the beginning of 90s, particularly dynamic development of wireless sensor networks (WSNs) has been observed [1]. Along with the increasing interest in wearable electronics, a marked increase in the availability of various types of sensors has been noticeable. Despite the fact that sensory technologies have been the subject of numerous studies for many years, the problem of their power supply in order to ensure stable and long-term operation has not been solved yet [2]. The commonly used batteries and energy storages are heavy, bulk, and rigid and are characterized by a short service life (work) time [3]. In view of the above, the research began to devote special attention to the sources of electricity alternative to battery power. Important areas of application of energy harvesters (EHs) are also battery power supply support systems [4], supercapacitors [5], and flexible batteries [6].

Currently, work on the development of EH micro-generators, which would reduce the need for cabling and

traditional batteries to power wearable electronic devices, e.g., sensors, access to which is considerably difficult, and sometimes even impossible, is ongoing all over the world. In the case of wireless sensor networks worn by human subjects, they are small generators that instead of fossil fuels use the primary energy present in the human environment, e.g. solar energy, electromagnetic energy, vibrations, thermal energy, or radio frequency, to produce electricity. The user of wearable electronics can also be a potential source of power; depending on the nature of the activities performed by the user, active and passive methods of energy harvesting are distinguished. Active energy harvesting takes place when the user of wearable electronics must perform a specific work to power the device. On the contrary, in the case of passive methods, the energy is produced as a result of typical vital functions or activities performed every day (breathing, heat emission, blood pressure, etc.) [7, 8].

EH microgenerators usually have dimensions ranging from one to a few inches and are used to power small devices,

such as sensors or sensor nodes. Therefore, the use of alternative energy sources eliminated the need for periodic charging or replacement of the batteries [9]. In the case of battery-powered devices, a problem of limited duration of functionality occurs. Therefore, the user is often forced to carry an extra set of batteries, which is associated with additional weight which adversely affects the convenience and comfort of the user [7]. Alternative energy sources do not require as frequent exchanges as is the case of the batteries. This is only necessary in the event of their failure, e.g., as a result of their use. In addition, an EH micro-generator can be combined with traditional energy sources of reduced capacity and dimensions, supporting in this way their power supply. This type of solution allows the power autonomy of electrically powered devices to be enhanced, while enabling their miniaturization [9].

Although there are a lot of research studies aimed at developing new EH, relatively few of them concern work on their implementation in the clothing structure and the tests of their effectiveness in the foreseeable conditions of use. In view of the above, it was decided to focus on the analysis of the state of the art in that area of implementation of alternative power sources in clothing, with particular attention to the advantages, disadvantages, and limitations in the application of EH.

2. Energy Harvesters in Wireless Sensor Networks

Wireless sensor networks worn by humans are one of the main areas of use of miniaturized EH, with the energy demand of a single network node differing according to the operating mode of the device [10–12]. The literature review indicates that, in the standby mode, the energy demand does not exceed a dose of several μW , and during measurements, it is approximately $100\ \mu\text{W}$, while during the data transmission, it ranges from 0.1 to 1 mW. These values clearly show the potential for application of miniaturized EH as the power source of an autonomic measurement sensor node [4]. A sample topology of a power supply solutions based on the EH is shown in Figure 1.

It is assumed that an EH generator should be equipped with appropriate electronic systems to manage the produced energy. This is due to a significant variability in terms of types, time courses, the parameters of energy quantities obtained at the output of EH transformers, and the performance time of the sources themselves. In order to guarantee proper functioning of the measurement node, e.g., the sensor, conditioning the amount of electricity produced by using the EH transformer in order to provide the proper power supply voltage is necessary. In the case of sources that are not able to deliver energy in a continuous manner (e.g., photovoltaic or kinetic sources based on vibration energy), the use of energy storage devices (e.g., batteries, accumulators, and supercapacitors) is required, which only in the next step will supply the energy to the specific measurement node in a controlled manner.

Given the above, in addition to the EH transformer systems, also energy management systems, energy storage

systems, and conditioners adjusting character of the consumed energy to the measurement node requirements can be distinguished in the structure of the generator. The required, common feature of these systems must be extremely low energy demand [4].

In order to use EH sources effectively, not only low-energy function regime of each of the generator systems is necessary, but also ensuring optimum way of obtaining energy is also necessary. The conditioning systems, whose role is to adjust the impedance of the EH transformer to the load, which is a prerequisite for obtaining a high power, are primarily responsible in this respect. In addition, it is necessary to apply an appropriate regulator adjusting the produced voltage to the receiver in the conditioner circuit.

As the main energy sources used in the miniaturized EH within wearable wireless sensor networks, the kinetic and thermal energy originating from the user and the radiation energy from the environment can be indicated [4].

3. Solutions Harvesting Energy from the Body Movements

Energy, which is generated during routine and seemingly insignificant movements of the body, seems to be promising as an alternative power supply to wireless, mobile networks, and wireless sensors [13]. In the case of alternative sources of electricity, that allow energy from the movement of the human body to be generated, we can distinguish the solutions based on the following phenomena: piezoelectric, electromagnetic, and triboelectric.

3.1. Solutions Based on Piezoelectric Effect. One way to generate electricity from the movements of the human body is the use of the piezoelectric phenomenon for this purpose. This phenomenon involves the occurrence of the resultant electric moment, that is, polarization of a piezoelectric crystal due to its compression or stretching in the specified direction. Mechanical deformation of the piezoelectric on the example of rectangular plates causes deformation of the electron shells and relative displacement of ions in the crystal lattice, which in turn leads to the generation of opposite electric charges on the opposite walls of the plate, the so-called simple piezoelectric effect. On the contrary, the exposure to an external electric field results in the deformation of the piezoelectric, the so-called inverse piezoelectric effect [4, 14].

Piezoelectric materials used for obtaining energy include mostly piezoceramics and polymer films produced on the basis of PVDF (polyvinylidene fluoride). Among piezoelectric ceramic materials, lead zirconate titanate (PZT), which consists of sintered titanium lead (PbTiO_3) and lead zirconate (PbZrO_3), deserves special attention [14, 15]. Piezoelectric polymers compared to piezoceramics are not fragile and are characterized by a higher tensile strength and lower rigidity. In addition, their manufacturing process is relatively simple and inexpensive. A strong piezoelectric effect is demonstrated by using polyvinylidene fluoride (PVDF) and its copolymers, e.g., with tetrafluoroethylene

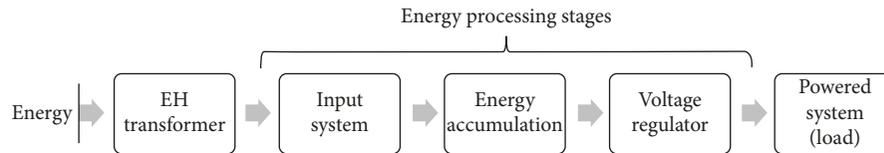


FIGURE 1: Topology of an exemplary power electronics solution (reproduced from Michalski et al. [4], under the Creative Commons Attribution License/public domain).

(TeFE) or trifluoroethylene (TrFE) [4]. Polyvinylidene fluoride (PVDF) is a very promising piezoelectric material because it has high mechanical and dielectric resistance, and it is also very resilient and responds quickly to changes in stress. For this reason, PVDF increasingly displaces piezoelectric ceramic materials [14]. An interesting work aimed at a highly flexible and efficient piezoelectric nanogenerator was presented by Zhang et al. [16]. By means of an addition of highly oriented BaTiO₃ nanowires, authors developed a nanogenerator that demonstrates an output voltage up to 0.9 V and an output current up to 10.5 nA when the nanogenerator was fixed on the human finger and the finger was bended. Another research direction regarding piezoelectric nanogenerators is a special 3-D structure of PVDF piezoelectric fabrics in order to ensure enhanced performance of generation of power and energy harvesting [17].

A sample clothing solution that uses piezoelectric elements to generate electricity is the two-piece underwear set proposed by Kim and Yun [8]. In these garments, spiral piezoelectric elements, consisting of a flexible core and polymer piezoelectric strip (made of a thin polyvinylidene (PVDF) film) wrapped around the core, have been applied. The piezoelectric elements are mounted in four locations, i.e., on the shoulder, the elbow, the knee, and the hip (Figure 2).

Clothing with integrated piezoelements was subjected to tests [8], which assessed the changes in length of the piezoelectric elements and the output voltage resulting from specific body movements, i.e., flexion and extension of the body in various joints, walking, push-ups, and squat exercise. The studies have shown that the greatest voltages possible to obtain from this type of clothing amounts to 3.9 V, in the case of a piezoelectric element placed on the elbow when the push-ups are performed; 3.1 V, in the case of element placed on the knee joint during walking; and 4.4 V, in the case of an element placed on the knee while performing squats. The maximum output power generated by the energy harvesting system of 0.2 mW was obtained during knee motion. To measure the output voltage and power during motion, the person wearing the garments was asked to repeat the specific movements while maintaining the motion frequency and the range of motion as constant as possible. The testing of the piezoelectric energy harvester itself has shown that it is able to generate the maximum power of 1.42 mW at an operating frequency of 1 Hz and a load resistance of 3 MΩ.

Piezoelectric elements made of PVDF were also applied in clothing by Yang et al. [18]. The view of clothing with a piezoelectric element is shown in the photograph (Figure 3). The design of these elements has been supported by the



FIGURE 2: A view of the garment with an energy harvesting system using the piezoelectric effect (reproduced from Kim et al. [8], under the Creative Commons Attribution License/public domain).

analysis of body movements using the motion capture techniques. The authors found that the piezoelectric element should have 160 mm in length; as with such size of the element, its largest elongation around the elbows and knees occurs. A width of the element at the level of 10 mm was selected, in order to ensure the required resistance to repeated mechanical influences.

Yang et al. [18] assessed three design variants that differed in terms of their spatial construction. A study carried out with the participation of volunteers demonstrated greater efficiency of piezoelectric elements with an increase in the elasticity of the textile material. It was observed that the greater elasticity of the material increases the stresses occurring in the garment and, consequently, increases the elongation of piezoelectric elements. It was also noted that appropriate structure of the garments can significantly affect the ability of piezoelectric elements to generate electricity. The best results were achieved in the case of clothing made of a material with the highest elasticity (with 5% of polyurethane fibers added), using a three-dimensional design of the piezoelectric elements placed on elbows and knees. Using the oscilloscope, the authors measured the harvested piezoelectricity as " V_{p-p} " and " V_{rms} ." " V_{p-p} " is the width of the maximum voltage output and " V_{max} " to the minimum voltage output " V_{min} ." " V_{rms} " means the root mean square (i.e., mean value divided by the square root) of the voltage output accumulated for 20 s. The tests showed that the



FIGURE 3: A view of the garment with a piezoelectric element at the elbow line [18].

output values of the piezoelectricity were higher in the knee joint than that in the elbow joint. In the case of knee joints, these values were $30.55 V_{p-p}$ ($6.61 V_{rms}$), while in the elbow joint, it is $22.64 V_{p-p}$ ($5.20 V_{rms}$). Moreover, the beneficial effects of increased frequency of body movements performed on the ability to produce electricity were confirmed. For example, in the knee joint, the output values of the piezoelectricity increased from $21.57 V_{p-p}$ ($5.12 V_{rms}$) for 1 Hz up to $39.53 V_{p-p}$ ($8.09 V_{rms}$) for 2 Hz. The authors also addressed a very important issue of the user's comfort while wearing clothes equipped with piezoelectric elements. For the proper functioning of the piezoelectric elements, tight fitting of the garments to the body is necessary, which in turn can cause mobility limitation.

The advantages of this alternative electricity generation method include the fact that the generation of energy is independent on the weather conditions, or on the location. On the contrary, the fact that the relative elongation of piezoelectric elements must be at least 20% to obtain the output voltage at the level sufficient for practical applications is a disadvantage. It should also be noted that, in this kind of solutions, the selection of the flexibility of materials intended for both the garment and the piezoelectric element is very important [8]. In addition, a key parameter is the degree the garment fits to the body and its construction [19].

3.2. Solutions Based on Electromagnetic Phenomenon.

Electromagnetic generators are based on the structure of bars vibrating in a magnetic field, forming an inert mass with permanent magnets and coils attached to it. The frequency of operation and the amplitude of vibrations are specific to each application, and therefore, the generator must be individually adjusted to these parameters. High efficiency of the conversion of mechanical energy into electricity is

achieved by optimizing the design of the electromagnetic circuit (e.g., the shape and size of a magnet and thickness of the air gap) [4].

An example of a solution that uses an electromagnetic field for generation of electricity while walking may be the electromagnetic generator described by Terlecka et al. [13]. This is a device of flat construction consisting of an induction element and an arc-shaped magnet. In order to determine the optimal placement of the aforementioned generator in clothing, the authors conducted performance tests on the treadmill. Seven locations where it would be possible to place the generator were tested (Figures 4(a) and 4(b)). The magnets were marked with orange, and the inductive elements with blue. Figure 4(c) shows 3 locations, in which the energy generated when walking on the treadmill was the highest. The best result of mean power of 0.50 mW was observed at the speed of motion 6 km/h when the electromagnetic generator has been placed in the men's insulated outerwear at the anterior superior iliac spine level. Over two and a half times less power, but still high, i.e., 0.18 mW, was obtained in the case of jeans at the knee level and at the speed of motion 4 km/h. Moreover, the tests carried out by Terlecka et al. [13] on users wearing insulating clothing with an electromagnetic generator showed that the double increase in the movement speed, i.e., from 3 km/h to 6 km/h, caused the generated power to increase over two and a half times, i.e., from 0.181 mW to 0.502 mW.

Eglite et al. [20] developed a prototype of a men's jackets equipped with special pockets and holes for incorporation of elements of the electromagnetic generator. The main challenge was to prevent a significant increase in the weight and dimensions of the garment and to ensure the user's freedom of movement. The distribution of elements of the generator in the garment was attained on the basis of experimental trials while walking. In this way, the exact trajectory of the

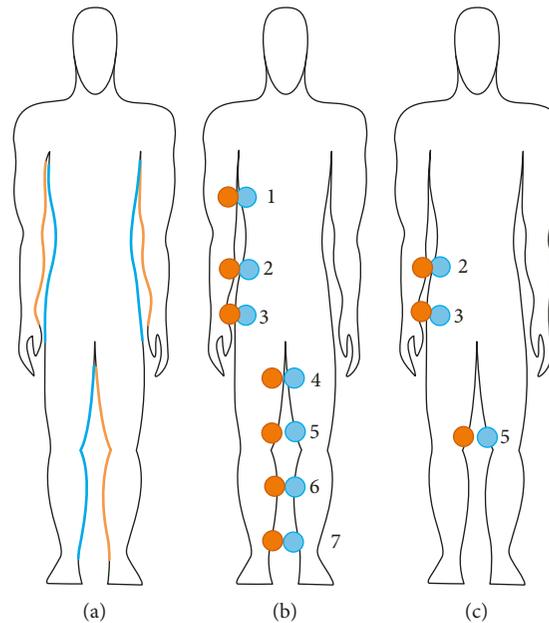


FIGURE 4: Location of the individual parts of the electromagnetic generator: (a) possible areas of application, (b) primary test locations, (c) selected locations of retesting (reproduced from Terlecka et al. [13], under the Creative Commons Attribution License/public domain).

magnet movement, which was optimized so that it coincided with the center of symmetry of the magnetic coil system, was obtained. The impact of the location of the coils in relation to the side seam of the jacket and of their number on the value of the generated voltage was also assessed during the study. Moreover, it turned out that the thickness of the clothing layers has a big impact on the generated energy. The best effect was obtained for clothing with a thin lining. The average generated energy then amounted to 42.83 mJ. The use of too thick lining or its lack caused a much lower energy generation, i.e. 11.53 mJ and 2.15 mJ, respectively. Eventually, it was decided to use the system of 3 coils connected in series on the right side of the jacket and 2 coils on its left side. These coils were placed in the pockets closed with waterproof zippers, and the magnets were fixed in flaps sewn on to the bottom part of the sleeve, closed with plastic snaps (Figure 5). The application of plastic rather than metal snaps is important because the presence of any metal parts could interfere with the proper operation of the generator. In view of the fact that, during the experimental trials, a positive amount of energy was generated, and it was decided to integrate in the garment not only an electromagnetic generator, transforming the energy of body movement to electric energy, but also a system for the storage of the produced energy. The saved energy can then be used to charge portable devices or to power the sensors of small capacity (e.g., temperature sensors, GPS, or sensors monitoring the health condition of the user).

An undoubtable advantage of such a method of energy harvesting is the possibility to place the generator in any location, without interfering with the structure of the clothing material (the generator can be glued or sutured on the surface of the garment). In addition, elements of the generator are small and flat, so they do not affect the reduction of comfort and convenience of the garment use.

Every movement of the user's body is used in the process of obtaining energy, so it requires no extra effort (obviously, as the movement speed increases the amount of produced energy and the power generated increases, as Terlecka et al. [13] mention in the publication).

A disadvantage of such a method of obtaining energy may be the fact that elderly people, who have problems with moving, could also have a problem with the production of a sufficient amount of energy. That is why electromagnetic generators would be recommended for athletes rather than for elderly people. In addition, it is noteworthy that the amount of power produced by the generator is strongly dependent on the position of the user's body, the kind of gestures performed, the walking speed, the amplitude of waving the hand, and the thickness of the textile package of which the garment has been manufactured.

3.3. Solutions Based on Triboelectric Phenomenon. The fact that fabrics accumulate static electricity under the influence of their contact and friction has been known for a long time. The term static electricity means the phenomena accompanying the emergence of unbalanced electric charge on the materials with low conductivity (dielectrics and insulating materials). These charges produce around them an electrostatic field, and the higher the intensity is, the higher the value of the charge is. If an object is placed in the electrostatic field, unbalanced electric charge may appear on its surface. For many years, the transmission and application of the accumulated charge to power external devices was a problem. However, owing to the use of materials of different polarity and charge accumulation capacity, as well as the introduction of a gap between them, utilization of random mechanical energy and its processing into electricity has become possible [21–23].

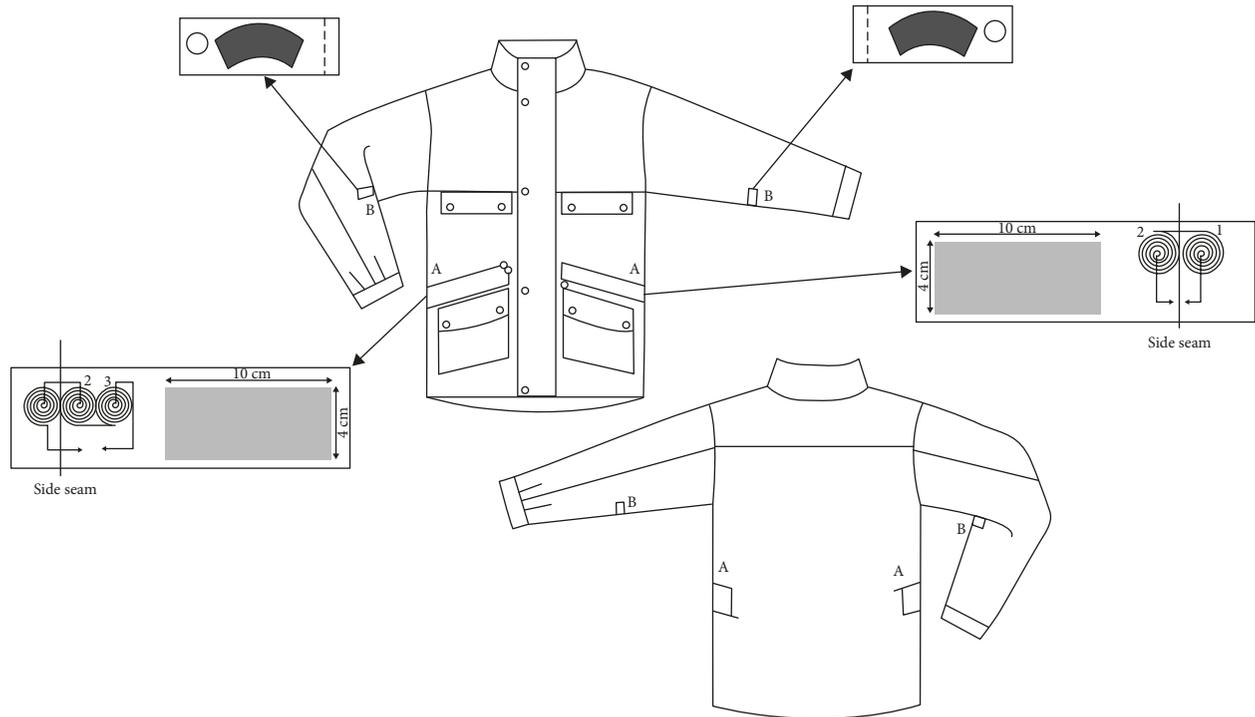


FIGURE 5: A technical drawing of the jacket with an indication of placement of the individual elements of the electromagnetic generator. A: location of the coil and accumulator; B: location of the permanent magnet (reproduced from Eglite et al. [20], under the Creative Commons Attribution License/public domain).

Energy based on the phenomenon of electrification due to the contact is obtained via the triboelectric generators. Generators of this type consist of two different materials, one of which is the electron donor and the other the electron acceptor. When the surfaces of both materials get in contact, the electron donor (e.g., glass or nylon) will transmit the electrons to the material which shows a higher electronegativity (e.g., silicon or teflon). Then, when these materials are separated, one of them (the donor) will take over the electrons and become negatively charged, while the other will lose them, thus obtaining a positive charge (the acceptor). If electrodes are attached to the electrified outer edges of both materials, which are then connected with each other, a current flow will occur. It will be recorded until equalization of the level of electrons in both materials. To obtain a high transfer of the charge, the positions of the materials in the so-called triboelectric series table must be as distant from each other as possible [22]. In order to increase potential areas of applications of the triboelectric nanogenerators, researchers look for a solution ensuring low device processing cost and high electrical output. Dudem et al. [24] faced this issue by employing a microgrooved architected (MGA)-poly(tetrafluoroethylene) (PTFE) and aluminum as triboelectric materials with opposite tendencies. The authors confirmed good electrical properties of the developed triboelectric generator in a robustness test, in which its output power was used to drive light-emitting diodes and portable electronic devices.

Jung and his team [25] proposed an integrated clothing system to detect the user's falls, powered with the use of alternative energy sources. The system consists of flexible

power supply devices (a triboelectric generator and a lithium-ion battery) in the form of wrist bands connected to a data-processing microcontroller, 3-axis accelerometer to detect the falls, and a Bluetooth module for data transmission. The material used for the electrodes of the triboelectric generator and the connection between the battery cells is flexible conductive nylon (C-Nylon). The surface of one of the nylon electrodes is coated with ethoxylated polyethylenimine (PEIE), which regulates the function of the generator and maximizes its performance. The other electrode is coated with silicone (Ecoflex®). During the movements of the clothing of the user, the two constituent materials of the generator come into contact, which results in the presence of friction. As a result of the subsequent separation of the materials, positive and negative charges are generated on the different surfaces as a result of contact electrification. The electric energy obtained from the generator through body movements (waving the hand) charges in a continuous manner the flexible lithium-ion battery, simultaneously increasing its working time. The integrated power supply system drives the 3-axis accelerometer and the associated electronics, which record the movements of the human body and send them wirelessly. After an unexpected fall, the software distinguishes the fall signal and sends an alarm to the mobile external device. Such a wearable fall detection system presents a new opportunity to quickly provide assistance to persons who have fallen down or have lost consciousness, especially in the case of elderly persons.

Seung and his team [26] developed a fully flexible, foldable, and nanopatterned wearable triboelectric generator

(WTNG), with high power generation efficiency and high mechanical strength. Two textiles coated with silver (Ag), one of which (i.e., the lower one) was modified by additionally covering with zinc oxide (ZnO) nanorods and then in polydimethylsiloxane (PDMS) solution, were used as active triboelectric materials. The nanopatterns obtained in this way on the lower textile material allowed the effect of electrization of both generator materials to be reinforced by increasing the contact surface of these materials, thereby increasing the friction. The studies carried out by the authors have shown that the nanopatterned PDMS-based generator produces electric current of high voltage (120 V) and intensity (65 μ A), while the generator without the nanopatterned PDMS coating produces a voltage of 30 V and a current of 20 μ A only. Very high voltages and currents, 170 V and 120 μ A, respectively, were obtained with a 4-layer WTNG. These values were obtained by applying compressive force (10 kgf) perpendicular to the WTNG using a mechanical force stimulator. Further increase of the compressive force did not significantly increase the output voltage and output current. It was found that, even after 12,000 work cycles the generator retained its electrical properties since there were no significant differences in the output voltage of the generator. These results confirm its excellent mechanical strength as well. To demonstrate the operation of the WTNG as a power source for wearable electronics, the authors installed an LCD screen, 6 LEDs, and a car remote control in a “smart self-powered jacket.” The function of the aforementioned electronic devices was demonstrated successfully using only the power output from the WTNG without any external power supply sources.

The advantages of the generators that transform triboelectric energy into electricity is the ability to generate power at any time; regardless of weather conditions, this energy is produced through the formation of electric charges between the two substrates during each body movement (e.g., while walking or waving the hand). Such generators do not have to be fitted directly in the clothing, and they may be supplied in the form of clothing accessories, e.g., bands or sleeves, put on the body.

The disadvantage of triboelectric generators, as is the case with other generators harvesting energy from the movement of the user, is the fact that the amount of energy produced depends on the intensity of movement. Movements with the higher impact and/or frequency (e.g., running versus walking) increase the power generation of the TEG. The triboelectric generator would rather not be useful to supply the energy to the electronics worn by patients or the elderly people because this type of generator requires a significant physical effort on the part of the user. In the case of this type of energy harvester, the characteristics of the materials from which the generator has been manufactured, and especially their area of contact, which determines the friction force, are very important.

4. Solutions Harvesting Energy from Temperature Differences

Direct conversion of heat energy into electricity is possible with the use of thermoelectric generators, so-called thermoelectric generators (TEGs) [27]. The most important

thermoelectric phenomena used to generate electricity include Seebeck, Peltier effect, and Thomson effects [28].

The Seebeck effect involves the formation of electromotive force in a circuit that contains two metals or semiconductors, at the time when their connectors have different temperatures [28]. In the atomic scale, temperature gradient causes the diffusion of current carriers from the hot to the cold side. Under ideal conditions, when the majority charge carrier is an electron, the size of the voltage produced is directly proportional to the temperature difference between the connectors, and the difference in the Seebeck factor (thermoelectric coefficient, characteristic of the material) between the materials of which the contacts are made is shown as follows [28]:

$$V = (S_B - S_A) \cdot (T_2 - T_1), \quad (1)$$

where V is the voltage generated between the connectors; S_A and S_B are the thermoelectric coefficients; and T_1 and T_2 are the temperatures of the connectors.

The Peltier effect is a thermoelectric phenomenon opposite to Seebeck effect, and it is now involved in generation of electric power. It involves absorbing the heat on one of the connectors and passing it on the second one under the influence of the current flowing through the circuit. The amount of heat transported depends on the connector materials and their temperature and current density. The temperature difference increases with a greater difference in the thermoelectric capacity (the Seebeck coefficient) of materials and with the increase of the current density. The average energy of the electrons involved in the conduction of electricity depends on the band structure of the material, the concentration of electrons, and the mechanism of their dispersion and, therefore, varies in different conductors. The electrons, moving from one center to another, give up excess energy to the surrounding atoms, or at the expense of these atoms supplement their energy deficiency (depending on the direction of the current flow) [28, 29].

Thomson's effect involves the release or absorption of heat during the current flow through a homogeneous conductor, in which there is a temperature gradient [30]. Whether the thermal energy is absorbed or released in the specific conductor depends on the direction of the current flow relative to the direction of the temperature gradient.

The three phenomena outlined above are interdependent and always occur together. The temperature difference of the contacts of two different metals that make up the thermocouple generates in the circuit the Seebeck thermoelectric force, which, in turn, forces the flow of the current causing the Peltier release and absorption of heat. In each of the conductors, the temperature difference causes additional heat flow resulting from the Thomson phenomenon.

The Seebeck phenomenon has been used, i.e., in the Peltier cells, to produce electric current. A Peltier cell (Figure 6) is a semiconductor thermoelectric element, made up of two ceramic plates, mounted in parallel to each other, between the planes of which there are alternately stacked “n” and “p” type semiconductors. The semiconductors, made of bismuth telluride with appropriate additives, are in electrical terms connected in series, with copper plates. Bismuth

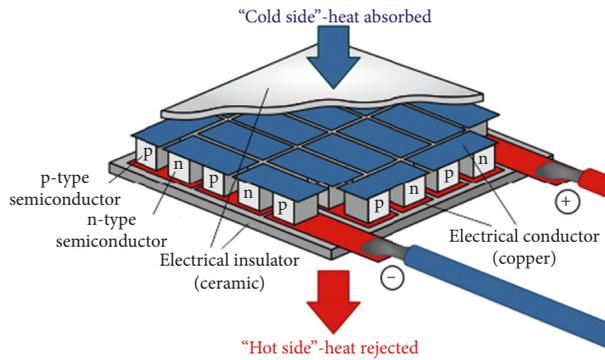


FIGURE 6: The construction and operation principle of the Peltier module.

telluride and antimony telluride alloy are the most commonly used thermoelectric materials because of their high efficiency at room temperature. These materials are also easily deposited in thin films in order to ensure flexibility of the module [31, 32]. The heat is absorbed by the cold side of the cell, goes through the Peltier module, and is emitted by the hot side of the cell. An electric current is generated from the beginning of the heat “flow” [4].

Leonov [33] has conducted a study aimed to identify the optimal (in terms of the generated energy) location of thermoelectric elements (thermocouples) in clothing and their design. Research shows that the best locations for thermoelectric energy sources (TEHs) can be the head, the torso, and the zones situated close to the arteries.

The author compared the power generated by using TEH depending on the method of its mounting in the garment:

- (1) TEH directly exposed to ambient air
- (2) TEH place under a cotton shirt
- (3) Approximately 5–10 mm air space between the cold plate of the thermocouple and the shirt fabric

It turned out that, in cases 1 and 2, similar power values at the level of approximately $80 \mu\text{W}$ were obtained. In turn, the presence of the air gap (case 3) resulted in a significant reduction in the amount of generated power by approximately a half compared to cases 1 and 2. Therefore, it was concluded that hiding TEH under the clothing material is beneficial from the point of view of the generated power, provided that the shirt fabric is in close contact with the cold plate of the thermocouple because the shirt material plays the role of a radiator (the heating element) for the TEH.

In another solution, to the inside of the cotton shirt, a piece of carbon fabric is glued, to which, in turn, the TEH cold plate has been attached. Thanks to the carbon fabric with the ability to distribute heat, a 30% increase in the generated power amount in relation to the solution no. 2 was obtained.

The last of the proposed solution involved the addition of an extra layer of textile, allowing the TEH to be hidden in the garment completely, thus providing comfort to the user. At the same time, the thickness of the thermocouples was reduced to 3.5 mm. Although reducing the thickness of these elements increased adverse heat flow, it influenced the

increase of their acceptance by the users. In total, the shirt was fitted with 16 thermocouples. All were located on the front of the garment.

Performance tests of the shirt were conducted by measuring the power generated by the implemented thermocouple under different conditions: indoors (on the office), outdoors, in a static position, and while walking. Better results were obtained when moving, which is related to the forced air convection, and not to an increased metabolic rate. An average power of 1 mW is measured in the office at 22°C , doubled when the person walked in a corridor. Similarly, under outdoors conditions at an ambient temperature of 17°C , the power also doubles, i.e., it increases to 2 mW in a standing or sitting person and to 4 mW in a walking person. It was also found that better results would have been obtained if the thermocouples were continuously pressed close to the skin. The extra layer of fabric between the skin and the hot plate material, although it can negatively impact on the generated power, provides more comfort, especially in the case of sweating.

Leonov [9] designed a few years earlier a shirt with an electrocardiogram (ECG) recording system, supplied with a battery that is continuously charged with energy harvested from the heat emitted by the user’s body. Energy power consumption by the energy-saving ECG system is within 0.44–0.5 mW, depending on the sampling frequency. This frequency is set automatically, depending on the available power. 14 thin 6.5 mm thermoelectric generator (TEG) modules with external metal plates of 3×4 cm dimensions, acting as radiators, are implemented in the garment. The TEG module was made of two plates: hot and cold. Between these plates, thermopile is placed. TEG is filled with the material with a thermal conductivity much less than that of air. Because of fragility of thermoelectric materials, in the device between the plates, there was necessary to use the rigid supports in the form of pillars and an encapsulating wall. These modules are arranged only in the front of the shirt on its outer side and take up less than 1.5% of its total area. The shirt is also equipped with two silicon photovoltaic (PV) cells of 2.5×4 cm dimensions, placed on its shoulders. Thus, there are two charging circuits, one from TEG and the other from the PV cells, which are connected to the power management module. The photovoltaic cells (PV) have been added to the system because if the shirt is not used for several months, the battery may undergo self-discharge. Therefore, to maintain the electronics contained in the shirt in the functional condition, the shirt should be stored in an environment with light available at least periodically. The elements of this system, i.e., TEG, PV cells, and electronics, are further reinforced by the use of a waterproof casing, so the garment can be repeatedly washed and dried mechanically. The authors declare that these elements are able to sustain machine washing with drying cycle at 1,000 rpm.

Under office conditions, during regular sitting work, TEG usually generates power within the range of 0.8–1 mW at a voltage of 1 V. On the contrary, during the user’s movement, the energy production increases to 2–3 mW due to forced convection.

An advantage of power supply using thermoelectric generators is the ability to generate energy without any effort on the user's part. Thermogenerators are characterized by a long and maintenance-free operation, reliability thanks to the lack of mobile parts, and immediate switching to the operating mode. Although the generation of energy is influenced by many factors, e.g., ambient temperature, wind speed, thermal insulation of clothing, and human activity, it does not depend directly on the metabolic rate [33]. As it follows from the research, the best locations for thermoelectric energy sources (TEHs) include the head, the torso, and the zones close to the arteries [33]. Better results are obtained when the user is in motion (due to the air flow), but also sitting in the office, we are able to produce enough energy to power the sensors. The test results [33] indicated that the power generated by TEH is double high when the user walking than when standing or sitting. Another plus is the possibility of placing thermogenerators on the classic clothing purchased in the shop, they can be glued or sewned up, without interfering with the structure of the clothing fabric [9].

However, there are difficulties in the manufacture of a flexible TEG—thermogenerators usually contain metal parts, so in spite of their small size, they must be isolated from the user's body, to avoid discomfort associated with unpleasant feeling, i.e., cold, during skin contact with metal. Unfortunately, isolation of TEG from the skin, e.g., by means of a textile fabric, affects negatively the heat consumption, so less electricity is produced. Recently, significant research progress on flexible thermoelectric materials (including those based on a silk fabric) [34] and generators has been observed, especially in the field of conducting polymer thermoelectric materials, nanocomposites comprised of inorganic nanostructures in polymer matrices, and fully inorganic flexible thermoelectric materials in nanostructured thin films. However, a comprehensive review conducted by Du et al. [35] indicated that flexible TEGs still have many challenges to be solved before they can be widely used, such as optimization of technological conditions and process, stabilization of n-type conducting polymers and their corresponding thermoelectric composites, or keeping higher temperature gradient in the TEGs.

5. Solutions to Capture Electricity from Solar Radiation

The photovoltaic effect involving conversion of solar radiation energy into electricity in a semiconductor element was discovered by a French physicist Alexandre E. Becquerel in 1839 [31]. The photovoltaic cell consists of high-purity silicon, on which the potential barrier in the form of a P-N (positive-negative) interface has been formed. The incident photons produce a pair of opposite electrical charge carriers, electron-hole, which due to the presence of P-N interfaces are separated in two different directions. The electrons are transferred to the N and holes to the P part, generating voltage on the interface. Since the separated charges are excess carriers of the so-called infinite lifetime and the voltage on the P-N interface is constant, the interface under exposure to sunlight acts like a stable electric cell (Figure 7) [4, 31].

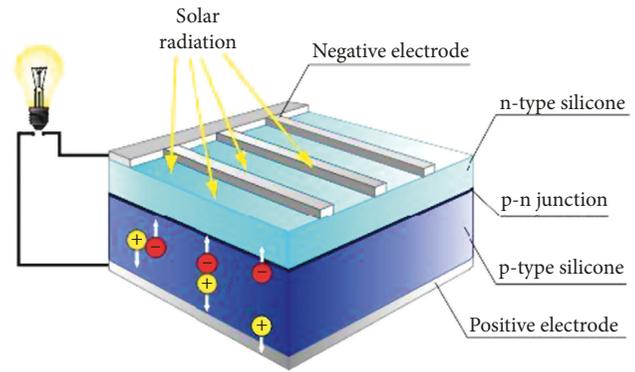


FIGURE 7: The construction of a photovoltaic cell.

An example of clothing using a photovoltaic cell is a T-shirt developed by Lee et al. [32], in which a small organic photovoltaic (OPV) textile-based cell has been implemented (Figure 8). This type of cell compared to film-based OPV cells show a much higher compatibility with textile products, as evidenced by the easy integration with fabrics.

The tests carried out by the authors [32] showed that both types of cells exhibit similar open circuit voltage (V_{oc}), i.e., 0.56–0.57 V. It is interesting that the short circuit current density (J_{sc}) from textile-based OPV (13.11 mA/cm²) was higher than that of typical OPV (11.9 mA/cm²). This is because textile electrode morphology could provide higher light scattering. In terms of efficiency, the textile-based OPV turned out to be slightly worse (1.79%) than typical OPV, where the efficiency was 2.97%. The developed organic photovoltaic textile-based cell, due to the advantages such as lightweight, small production cost, and ease of the manufacturing process, as well as no negative impact on the environment, would be a good solution for harvesting energy. The presented cell is small in relation to the T-shirt (a few cm²) and is built as a standard fabric—two systems of threads crossing each other. The advantage of this cell is, above all, its flexibility, owing to its construction could be integrated into clothing, without affecting the deterioration of the user's comfort. In addition, despite its small size, it is capable of producing power at the level of 13 mA/cm². The research shows that the cell demonstrates high reliability under mechanical distortion.

Another example of a garment that uses photovoltaic cells is the jacket with removable solar panels on the back, developed by Pvilion and Tommy Hilfiger (Figure 9) [36]. These panels provide energy to power electronic devices such as mobile phones or tablets. The solar panels are connected via a cable to a removable battery pack stored in the front pocket of the jacket. Thanks to the double USB port, it is possible to simultaneously charge two devices. The solar panel unit itself is made with flexible amorphous silicon technology, developed by Pvilion. When exposed to full sunlight, those cells can fully charge the battery pack which, in turn, can fully charge a standard 1500 mAh mobile device up to four times.

BOGNER and MUSTANG companies designed and produced a denim jacket with single-crystalline photovoltaic

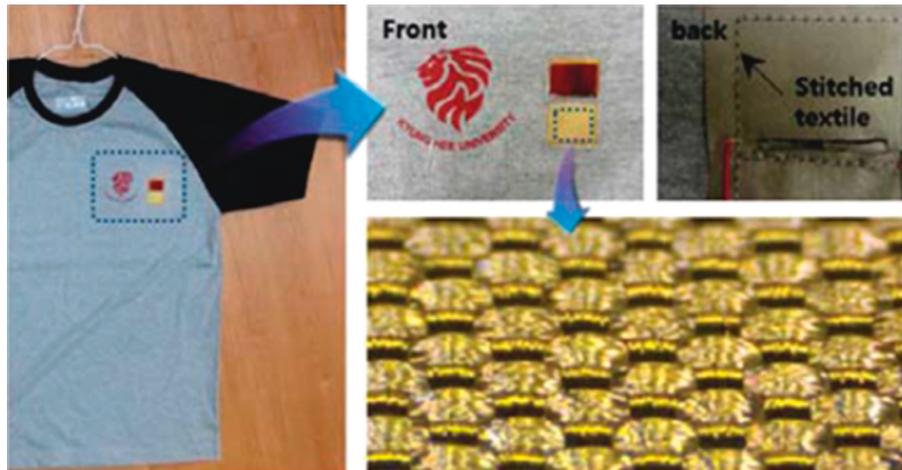


FIGURE 8: Method of integration of the photovoltaic cell with a T-shirt [32].



FIGURE 9: An example of a jacket with removable solar panels (Courtesy of <http://www.pvilion.com>) [36].

cells (c-Si cells), placed at the front of the jacket. Two modules, each consisting of 16 cells were used, which were connected like roofing shingles. They are used to power the LEDs placed along the sleeves. These photovoltaic cells are brittle, and therefore, they have been fixed onto a rigid metallic backplane that ensures their mechanical stability. Their efficiency exceeds 20% [37].

As part of the SOLARTEX project, several prototypes of clothing with solar cells have been developed. An example is the TEMPEX jacket, in which bright photovoltaic-powered warning lights complement the built-in passive safety features, e.g., for street construction workers. In turn, the KANZ company designed a coat for children, which aims to increase their visibility in the dark. The implemented photovoltaic cells are used to power LEDs placed all over the coat [37].

Another example is a T-shirt with the system designed to measure the heart rate, respiratory rate, and movements of the body, powered by a flexible solar panel, which is placed on the back of the T-shirt [38]. The mean power

consumption is very low, about 17 mW. It can be used for elderly people, who, by virtue of their age, require continuous control of vital functions. Besides, the T-shirt can be used by athletes. With it, the users are able to control their performance and strive to improve it. The PowerFilm Solar panels were applied in the shirt. The PT15-150 panel (PowerFilm WeatherPro Series) was selected. This panel is ideal for permanent wear and use in a variety of weather conditions. It has a UV-resistant surface. In addition, its edges have been additionally sealed to protect against adverse weather conditions. Its undoubted advantage is also washability. With 270 mm × 175 mm dimensions and 66.5 g weight, it can produce a voltage of 19 V and current of 100 mA with full sun. Even in the cloudy day in shadow areas, when the panels were positioned to the horizontal plane (0°), the generated power was sufficient to supply the wearable device during all the day. Under such conditions, the generated power did not drop below 20 mW, and for the most part of the day, i.e., between 10:30 and 16:00, it remained at the level of approx. 40 kW.

Brogan and his associates [39] developed a jacket that has both photovoltaic cells and thermoelectric generators, so this jacket can collect solar energy and energy generated by the temperature difference: between the user and the environment. The jacket has an integrated system capable of harvesting energy, consisting of the following items: 16 photovoltaic (PV) cells, 12 thermoelectric generators (TEG), and two AAA NiMH batteries that store energy collected by using the PV and TEG elements. In this jacket, the Texas Instruments chips BQ25504, which are intended for application in alternative energy sources used on a small scale, were implemented for management of the energy obtained from PV and TEG sources. The chips have a low-power converter allowing the output voltage to be increased. This model was selected because of its low power, simplicity, and adaptability. It can manage the input voltage of only 330 mW and work with input voltages from 80 mV to 5.5 V.

The PV cells are arranged in the groups of 4, in 4 different places on the jacket (the chest, back, and the right and left shoulders). The choice of these sites was determined by the fact that the cells in these places are exposed to light in a similar degree. In each of the areas, the cells are connected in parallel and have one power management circuit (PMC), which allows the accumulated voltage to be adjusted to charging of the battery and/or operation of the photovoltaic cells.

In the jacket prototype, thermogenerators (TEGs) in the form of Peltier cells (model TEC1-12709) were used because they are characterized by good performance with a small temperature difference. The TEGs are placed on the jacket as follows: 6 units connected in series. The groups connected in this way are located in two places: on the front of the jacket and on the back.

The developed jacket model is a winter jacket detachable lining. The PV cells are placed on the top layer of the garment, whereas the TEGs are placed in the lining. The batteries and the PMC are located between the lining and the outer fabric layer of the jacket [39].

As demonstrated by the research [39], the average power harvested by the photovoltaic system ranges between 475 mW and 500 mW on a sunny day. However, on very cloudy days and in full shade on full sun days, this value was reduced even to 140–220 mW. The maximum power generated by using TEGs was 1.25 μ W under full sun, and 0.5 μ W in the shade, so the energy from TEG was much lower than the energy provided by using PV cells due to the low-temperature gradient available within the jacket. The biggest advantage of solar energy is the fact that this energy is provided at all times, regardless of the user. However, the photovoltaic cells require constant access to the light [39].

The advantage of this kind of power is undoubtedly the fact that power generation is independent of the user. He/she can move or remain in a static position, and the energy generated from photovoltaic cells will be the same. In addition, the cells intended to power wearable electronics are characterized by small size and weight and are flexible, so they do not adversely affect the comfort of clothing.

The disadvantage of such systems is, unfortunately, the need for continuous access to the light. The amount of

energy produced is dependent on the intensity of the light. PV panels are able to function correctly both indoors and in the open space. However, the power they produce in indoor areas (or when the sky is heavily clouded) is insufficient to maintain the system.

6. Conclusions

Together with the progressive miniaturization of electronic systems and the development of the so-called wearable electronics, a demand for the source of electric power alternative to batteries has emerged. In the case of electronic equipment/systems incorporated in clothing as energy harvesters (EHs), the solutions, capturing energy from the movement of the body (based on piezoelectric, electromagnetic, and triboelectric phenomena), from temperature differences and solar radiation can be used.

The EH solutions based on the piezoelectric phenomenon work most efficiently in the garments, fitting tightly the user's body, made of elastic materials. Such clothing must exert a pressure on the user's body for correct functioning of the piezoelectric element. At the same time, it should be noted that too much pressure of the garments or of clothing accessories (e.g., bands) on the body can cause a discomfort to the user. Additionally, the amount of power generated depends on the frequency of movements and the mobility range.

In the case of alternative sources of energy based on the electromagnetic phenomenon, like in the case presented above, to generate the energy, it is necessary for the user to move, but simple movements performed every day, i.e., waving hands, marching, and running, are sufficient. This depends on the location of the electromagnetic generator items in the garments. These items are usually lightweight and have a flat construction; therefore, they should not cause discomfort to the user. As it follows from the literature data, the power generated by using an electromagnetic transformer implemented in clothing may reach the value of approximately 0.50 mW while the user is marching at 6 km/h speed, which is enough to power a wireless sensor node.

In the case of triboelectric generators producing energy based on the electrification phenomenon, the type of materials used for their production is important. The best effect is achieved by using materials as remote as possible in the triboelectric series table. The research reports already contain information concerning triboelectric generators based on textile materials, more friendly to the user's skin and more compatible with clothes than the previously used materials. A ready-made solution of miniaturized triboelectric generators which could be used in clothing is rather difficult to obtain in the market.

The advantage of all of the above EH generating energy from the body movements is their ability to generate energy regardless of the weather conditions and the location of the user. In the case of solutions utilizing thermoelectric generators and photovoltaic cells, these factors are very important, so special attention should be paid to them in the process of design of clothing with their participation.

In the literature, information on thermoelectric generators using the temperature differences between the human body and the environment to power simple devices incorporated in clothing often appears increasingly. These generators can be used at both indoors and outdoors, although a better effect is obtained in an open space, where there is a greater flow of air. The efficiency of the generator increases during the user's movements and when in use at lower ambient temperatures. The best locations for thermoelectric energy sources are the head, the trunk, and the zones close to the arteries.

Photovoltaic cells do not require any physical effort on the user's part to produce energy. However, constant access to the light is a prerequisite for their work. Their advantage is the flexibility, low thickness, and low weight. They are relatively cheap and easily available on the market.

In summary, each of the aforementioned alternative sources of energy has both disadvantages and advantages. Therefore, the selection of EH should be preceded by a detailed analysis of the conditions of use of the garments, their intended applications, the user's physical activity, and energy demand of the used electronic devices. However, a promising research direction is the development of flexible hybrid nanogenerators (e.g., combining a use of triboelectric and piezoelectric effects) that can enhance energy harvesting and expand their application areas [40].

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The publication has been based on the results of Phase IV of the National Program "Safety and working conditions improvement," funded in the years 2017–2019 in the area of Research and Development work by the Ministry of Science and Higher Education/the National Centre for Research and Development, and the program was coordinated by the Central Institute for Labour Protection–National Research Institute.

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