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On the Cutting Edge of Safety:
Wearable Smart Sensors for Workplace Applications

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Abstract

Recent advancements in sensor technologies have the potential to enhance workplace safety by enabling continuous, real-time monitoring of workers' health and safety. These developments assist in risk management and injury prevention, contributing to a reduction in workplace-related incidents and health issues. This thesis conducts a comprehensive analysis of wearable sensor technologies, with emphasis on flexible electromechanical sensors used for human motion monitoring. It explains their operating principles, characteristics, and key parameters. Special attention is given to flexible piezoresistive strain and pressure sensors, which are suited for integration into textiles employed in personal protective equipment (PPE) and smart garments and have desirable properties that make them ideal for use in adverse work conditions.

The study focuses on the main materials and fabrication techniques used in a few key examples and showcases their performance in practical scenarios. Additionally, the thesis discusses the process of signal acquisition and processing from piezoresistive sensors.

Finally, the thesis explores several applications of smart sensors in occupational safety, highlighting their role in mitigating workplace-related incidents and health issues.

Abstract in italiano

I recenti progressi nelle tecnologie dei sensori hanno il potenziale di migliorare la sicurezza sul lavoro, consentendo un monitoraggio continuo e in tempo reale della salute e della sicurezza dei lavoratori. Questi sviluppi assistono nella gestione del rischio e nella prevenzione degli infortuni, contribuendo a una riduzione degli incidenti e dei problemi di salute legati al lavoro. Questa tesi conduce un'analisi approfondita delle tecnologie dei sensori indossabili, con un'enfasi sui sensori elettromeccanici flessibili utilizzati per il monitoraggio del movimento umano. Spiega i loro principi di funzionamento, caratteristiche e parametri chiave. Un'attenzione particolare è data ai sensori piezoresistivi flessibili di deformazione e pressione, che sono adatti per l'integrazione nei tessuti utilizzati in dispositivi di protezione individuale e indumenti intelligenti, e possiedono proprietà desiderabili che li rendono ideali per l'uso in condizioni di lavoro avverse.

Lo studio approfondisce i materiali e le tecniche di fabbricazione utilizzati in alcuni esempi chiave e mostra le loro prestazioni in scenari pratici. Inoltre, la tesi discute il processo di acquisizione ed elaborazione del segnale ricevuto dai sensori piezoresistivi.

Infine, la tesi si conclude con l'esplorazione di varie applicazioni dei sensori intelligenti nella sicurezza sul lavoro, evidenziando il loro ruolo nel mitigare gli incidenti e i problemi di salute correlati al lavoro.

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Chapter 1 – Introduction

With the recent digitalization of the industry, commonly known as smart manufacturing or simply Industry 4.0, an ever-growing attention is related to the use of sensors and digital technologies for the monitoring of occupational safety and risk management. The evolution of cutting-edge smart sensors and technologies holds the promise of assisting in the reduction of work-related risk factors for workers across all industries and the potential of saving lives.

This thesis focuses on some of these technologies and their applications, putting particular emphasis on wearable sensors integrated into smart clothing that can assess and mitigate risk factors in various ways.

In recent years, technological developments, changes in workforce demographics, education, and skill levels, alongside forced transitions during the Covid-19 crisis have increased awareness of psychosocial and emotional challenges, together with other work-related risk factors that can adversely affect mental wellbeing. Alongside these risks factors, classical ergonomic risks and physical risks like exposure to noise, vibrations, extreme temperatures or biological agents, have seen very minor or no decreases in the past 15 years, based on data from the European Working Conditions Survey (EWCS) and European Survey of Enterprises on New and Emerging Risks (ESENER) [1].

Since 1998, the European Union has seen an overall decrease in incidence of non-fatal and fatal work accidents of about 58%. Despite that, millions of workers suffer the human and financial burden of work related injuries every year, with about 44% of non-fatal accidents happening in one of the four major sectors: Agriculture, Manufacturing, Construction, Transportation and Storage [1], which are identified as the most dangerous industry sectors in the world [2].

And while the overall data reflects a generally positive trend, there are countries where such a trend is negative. In fact, in Italy, by the end of 2021 an increase of 25.9% in reported work-related injuries has been registered, compared to 2020. Similarly, by the end of 2022 the incidents registered were 25.7% more than those registered by the end of 2021 [3].

While numerous safety and health standards exist for the purpose of supporting the practical implementation of preventive safety and health measures, a strong need for better preventive technologies is often perceived, since this could have the potential of a strong reduction in accidents, and thus could contribute to a further reduction in the incident rates over the next years [1].

Specifically, Sensor-Based Safety Management Systems (SBSMS) can improve the various aspects of risk management processes and can help with the prevention and real-time monitoring of risk factors. A 2020 review by Asadzadeh et al. analyzing recent developments of smart technology in construction safety discovered a rise in the deployment of all the relevant techniques and technologies from the year 2016 onwards, indicating a move towards sensor-based safety management in the construction industry. These systems cover a wide range of hazards, from environmental-monitoring and location-tracking to detection of physiological state monitoring, detection of unsafe behavior and violation of safety regulations [4].

The actual SBSMS technologies documented in the literature are quite many and with functions, technologies, and scope often overlapping. One notable category of SBSMS technologies involves wearables, which are used in industrial environments to monitor employees' psychological and physiological factors, enhance operational efficiency, promote work environment safety and security, and improve workers' health [2].

Figure 1- Wearable devices in the industries [2]

Poor posture, ergonomics and fatigue are some factors that can contribute to increasing chances of incidents during work hours, but also long-term. For example, sustained poor spinal posture is associated with the development and worsening of many musculoskeletal disorders. It is hypothesized that long-term use of systems that encourage the correction of poor posture through biofeedback may instill correct postural habits and yield a decrease in the incidence of posture-related musculoskeletal disorders [5].

For this thesis, the main focus will be addressed only on wearable sensors embedded into clothing and PPE that can be used to track correct posture and ergonomics, worker movement and fatigue monitoring.

In the following chapters the category of Electromechanical Sensors will be first of all discussed along with their working principles, characteristics, and applications. The focus will then be addressed to Piezoresistive Strain and Pressure sensors that can be integrated directly into garments and that also have desirable qualities for hostile work environments.

Then, the basic methods of fabrication commonly used for these sensors and the electronic conditioning methods will be covered. And finally, some applications of these sensors in the field of occupational safety will be discussed.

Chapter 2 – Wearable Sensors for monitoring human motion

Despite the first wearable sensors being dated back to 1960s, with the need of monitoring astronaut's health continuously and transmitting the data back to Earth during the Apollo Space Program [6], commercial implementation of sensing technology didn't really took off until the last decades.

Advances in miniaturized electronics and the proliferation of smart-phones, connected devices and a growing consumer desire for health awareness are some of the factors that contributed to the explosion of wearable sensors technology [6].

2.1 Common wearable sensors technologies for tracking human motion

One of the most desirable characteristics for wearable sensors in work environments is that of being able to non-invasively measure the required biomedical information and transmit it. For gait and motion analysis the three following methodologies are the most common and prevalent in the market.

2.1.1 Inertial sensors

These sensors are usually composed of one or a combination of accelerometers, gyroscopes, and magnetometers that are usually placed above or below joints for tracking joint movement, walking speed and for rehabilitation. While it is one of the most accurate and precise methods of clinical gait analysis, these sensors suffer from drawbacks that limit its application in daily life, like its drift effect, sensibility to electromagnetic noise disturbance and the rigidity of the sensors themselves [7].

2.1.2 Optical fiber sensors

Optical fiber sensors (OFSs) are sensors composed of an optical fiber, a light source at the beginning of the fiber, and a photodetector to receive the intensity-attenuated light beam at the end. By bending the optical fiber with human movement, the light beam sent from one end will start bouncing in the fiber optics, thus losing energy through the imperfect medium. The attenuation of intensity of the sent light beam can then be used to quantitatively measure the amount of bending done during human motion. While these sensors are immune to electromagnetic noises, they suffer from low sensitivity that some techniques seek to improve upon by applying "teethlike" imperfections on the surface of the optical fiber [7].

2.1.3 Angular sensors or goniometers

Goniometers are often used for quantitative evaluation of the angular motion of joints. These are some of the most commonly used sensors in joint motion surveillance due to their simple mechanism. Their functional principle is based on that of strain gauges, which provide a change in their electrical resistance proportional to horizontal and vertical deformations. There are a number of flexible implementations of this principle in the literature that employ textile-based goniometers or even knitted piezoresistive fabric as sensors for various human motion monitoring applications [7].

2.2 Electromechanical sensors and their transduction-based classification

Electromechanical sensors, or Deformation sensors, convert mechanical strain caused in the material by a wide variety of external stimuli (e.g., bending, tension, compression, torsion or shear stresses) into an electrical signal through various transduction mechanisms. Together with a wide availability of materials and fabrication technologies that can be employed, these transduction mechanisms allow them to have some significant advantages over the other previous types of sensors, including negligible weight, the ability to seamlessly integrate sensors into daily garments, comfortability and even the ability to sense the stimuli at its origin where the signal is the strongest.

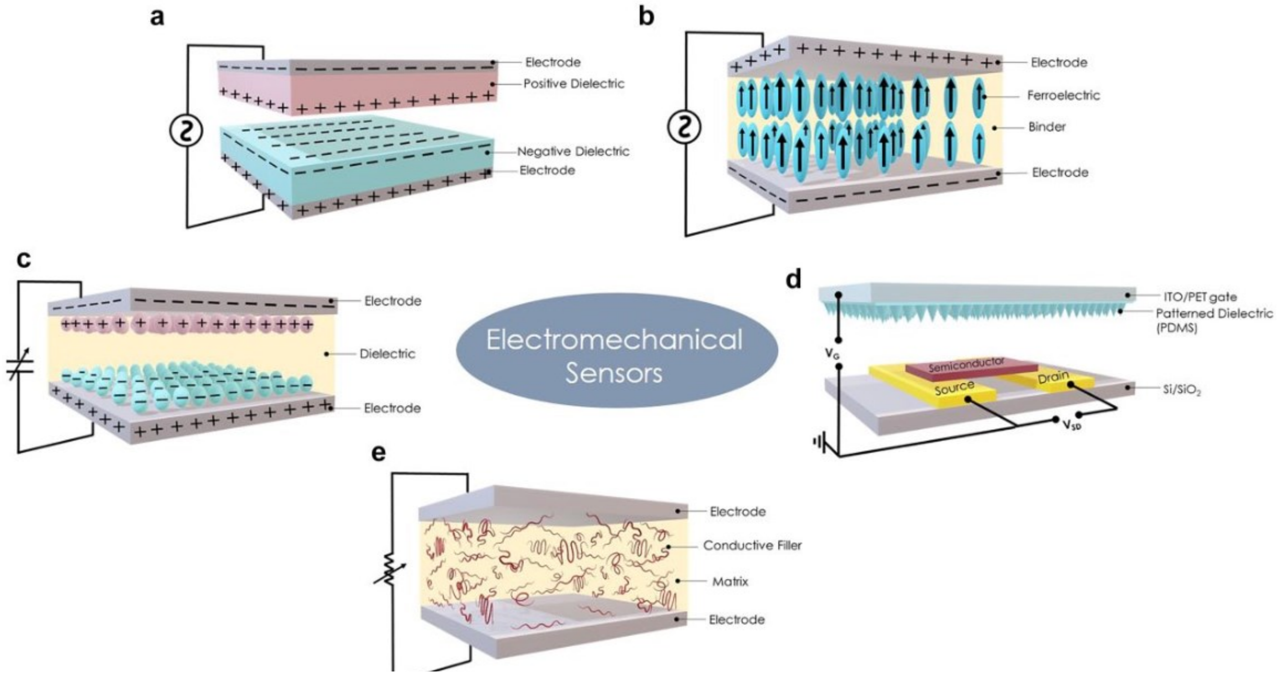

Figure 2 - Schematic illustration of electromechanical sensors: (a) triboelectric, (b) piezoelectric, (c) capacitive, (d) transistive, and (e) piezoresistive [7]

Despite inertial sensors, OFSs and Goniometers having demonstrated great popularity in clinical applications thanks to their high precision and accuracy, one of their main drawbacks is represented by limited flexibility of the major sensing elements integrated, usually made from rigid material, which can result in reduced sensitivity, comfortability, and durability. This factor contributes to limiting their use only in controlled testing environments like the clinical and laboratory settings, and not in unsupervised settings for long-term monitoring.

Differently from those sensors Electromechanical sensors represent the optimal candidate for long term monitoring in PPEs and other work-related garments since they can guarantee accurate and sensitive measurements of human motion monitoring in combination with limited obtrusiveness and improved ruggedness [7].

Based on their transduction mechanisms, Electromechanical sensors can be classified as Triboelectric, Piezoelectric, Capacitive, Transistive and Piezoresistive. Further distinction can be made between Pressure and Strain Sensors, based on the two major groups of mechanical stimulations that human body movements can produce, which are pressure and tensile forces.

2.2.1 Triboelectric Sensors

The triboelectric effect, also known as triboelectrification, is one of the most conventional phenomena that occurs in our daily life and the working principle for triboelectric sensors. The effect describes the phenomena of two materials becoming electrically charged after contact. Sensors that use this effect specifically measure the generated triboelectric potential through electrodes placed in direct contact with the active tribomaterials. When the electrodes change their length, the electrons flow in the circuit to compensate for the potential difference.

Triboelectric sensors have high sensitivity, do not have any power consumption and since they can be made with a wider range of sensing materials than sensors employing different sensing mechanisms, they can possess good biocompatibility and flexibility [8].

A recent implementation of these sensors that has become common is the Triboelectric Nanogenerator (TENG) which uses the triboelectric effect to generate electricity by physically manipulating two materials with opposite surface charges. As the working principle of this sensor also allows for power generation, and in some cases triboelectric sensors offer a higher output power density and energy conversion efficiency than other types of power generating sensing mechanisms [8], some implementations has seen the TENG made as an insole and used to harvest energy from human motion, thus allowing the creation of self-powered sensing devices[7]. Further developments allowed for the production of TENG textile fibers[9] that can be easily tailored into comfortable garments.

Another limitation that remained regarding these sensors is the need for skin-mounted solutions or to be embedded into tight-fitting garments. The realization of an all-fabric layered triboelectric sensor in which the tribo-charges were induced by the folding and compression of the textile itself removed this limitation, making them suitable for being tailored in everyday loosely-worn clothes [7]. In general, triboelectric sensors have been created using quantities of commercial materials, such as rubbers, plastics, elastomers and so on, becoming more common since the problem of power consumption of the sensing unit has been addressed [10].

2.2.2 Piezoelectric Sensors

Piezoelectricity is an intrinsic property of some materials that can generate an electrical charge proportional to the amount of applied mechanical stress [7], when they undergo tensile, compression or bending forces leading to a reorientation of the dipoles inside the crystal faces of the material.

Since material flexibility is necessary for fabrication of wearable electromechanical systems, the most typically used and widely available piezoelectric ferroelectric polymer material for these applications is polyvinylidene fluoride (PVDF). Proposed implementations of sensors based on PVDF piezoelectric sensors allowed for the production of sensible devices that can detect respiratory signals through a chest belt and hand gestures through subtle muscle movements of the wrist [7]. Besides the many synthesized organic and inorganic piezoelectric materials, natural alternatives exist that can be used as active materials for flexible sensors. One of these natural occurring materials is silk, which is widely available and a bountiful candidate for textile-based sensors. Another natural-inspired piezoelectric material used fish skin, which is composed of collagen nanofibrils which have piezoelectric properties [7].

Applications of this technology include skin-mounted sensors for tactile sensation, finger bending motion detection, arterial pulse pressure waveform measurement, detecting body movements and biomechanics characterization. Further implementations has seen this category of sensors introduced as temporary tattoos that can be used to monitor vital signs with high sensitivity [6].

Like for the triboelectric sensors, these sensors have the potential to be used for harvesting energy from human movement, allowing for self-powering sensing devices. One implementation by Zhu et al. has been seen in the fabrication of poly-L-lactide (PLLA) nanofibers on a comb electrode that transformed joint movement of the knee into electricity [7].

2.2.3 Capacitive Sensors

Capacitive sensors have gained popularity in recent years, thanks to their usage in consumer electronic touch screens that allow for good device sensitivity with low power consumption. Capacitive pressure sensors have been largely employed in consumer electronics and industrial applications, and more recently, with emerging wearable trends, they extend their applications to various human pressure-sensing interfaces, including electronic skin mimicking tactile sensation [6].

Based on the general functioning of a capacitor, a capacitive sensor is usually composed of two electrodes that sandwich together a dielectric material. Mechanical stimuli can be then converted into a change in capacitance C following the parallel plate capacitors equation:

$$C = \frac{\varepsilon A}{d}$$

Where ε is the dielectric constant, d is the distance between the plates and A is the overlapped area of the two plates [7], [10]. As these variables are altered by the external loads, this lead to the change of capacitive readouts [6]. The change in capacitance induced by an externally imposed deformation usually exhibits excellent linearity but low sensitivity, specifically when it comes to dielectrics with a large Young's modulus [7]. And since conventional materials lack the stretchability necessary for wearable devices, other materials must be employed.

The majority of capacitive flexible pressure sensors on the market today are based on elastomers like polyurethane (PU), polydimethylsiloxane (PDMS), Ecoflex (a biodegradable polymer) and others, which constrain future practical use by mechanical mismatches with human tissue and biocompatibility problems. Due to their inherent biocompatibility and low Young's modulus, hydrogels are seen as more promising than elastomers for the creation of future wearable pressure sensors [10].

In fact, besides pressure monitoring, other sensing modalities such as strain and bending measurements have also been achieved with capacitive sensors that employ hydrogel film for the electrode plates, highly stretchable, biocompatible and with self-healing properties [6], [7]. These properties make them suitable for human motion detection, like strain in the knee patellar reflex, and walking and running detection [7]. Recent tests performed with other materials and fabrication techniques, like piezocapacitive all-carbon sensors made using hierarchically engineered elastic carbon nanotube (CNT) fabrics, allow for capacitive sensors that can simultaneously detect heterogeneous versatile external subtle stimuli such as tactile, touch, temperature, humidity, and even biological variables [11]. These innovations extend the applications of capacitive sensors to human pressure-sensing interfaces and electronic skin mimicking tactile sensation [6], [7], [10].

2.2.4 Transistive Sensors

Transistive sensors are obtained by integrating flexible capacitive pressure sensors into organic field-effect transistors (OFETs).

Though they have limited performance, OFETs represent a low-cost alternative to their silicon-based counterparts, with improved characteristics in term of integration on soft polymeric substrates and applications in soft displays and bendable organic solar cells[12] . Compared to a typical silicon-based field-effect transistor, OFETs can operate stably even under water [13] and a flexible pressure sensor OFET designed for electronics skins has proved the capacity for multi-stimuli responses and a very low power consumption[7] making them ideal for wearable device applications. Though the OFET technology itself has existed since the 1980s, it is still under active development.

2.2.5 Piezoresistive Sensors

The main transduction mechanism for Piezoresistive sensors is Piezoresistivity, the capacity of certain materials to convert mechanical deformations into variations of electrical resistance. The working principle is based on the well-known equation of resistance for conductors:

$$R = \rho l / A$$

R is the electrical resistance, ρ is the electrical resistivity of the conductor, l is its length, and A is the cross-sectional area of the medium. By applying mechanical stress, the last two qualities of the sensor can vary, changing the electrical resistance measured [6], [7], [10], [14].

The simple structure design of piezoresistive sensors allows for low power usage, straightforward readout circuits and wide detection range, making them some of the most widely studied sensors [10]

Piezoresistive Sensors are usually divided into two categories, based on the type of applied stress, specifically *Piezoresistive Pressure Sensors* for mechanical compression and *Piezoresistive Strain Sensors* for tensile stress [7].

2.2.5.1 Piezoresistive Strain sensors

Determining the resistance change in a Piezoresistive Strain Sensor is determined by using the following the formula:

$$\frac{\Delta R}{R} = (1 + 2\nu)\varepsilon + \frac{\Delta \rho}{\rho}$$

Where ν is the Poisson ratio for the medium used and ε represents the strain [10], [14], [15]. Another significant factor that affects resistance is the contact resistance, which changes because of applied force and variation of area or geometry between the materials. For piezoresistive sensors though, the relationship between applied force and contact resistance allow for a wide range and good sensitivity of these sensors under low pressure [10].

Piezoresistive strain sensors are the most prevalent type of sensors between mechanoelectrical sensors, with different fabrication methods and materials suggested in the literature that allow for a wide range of capabilities including super elasticity, omnidirectional deformation sensing, high sensitivity, or high durability of the sensors [7]. Some notable examples of recent fabrication techniques for Piezoresistive strain sensors that can be used in textile integration will be covered in depth in the next chapter.

*2.2.5.2 Piezoresistive **Pressure** sensors*

Piezoresistive Pressure sensors on the other hand are usually used to detect with high sensitivity small pressure forces like touch or pulsatile blood. Unlike strain sensors, they are usually composed of two electrodes, with a nominal resistivity originating by their contact. The nominal resistivity can be modulated by increasing or decreasing the number of electrical contact points between the electrodes. This is done by simply applying pressure to the sensor. This pressure sensitivity is defined as

$$P_{sensitivity} = (\varDelta R/R_0)/\varDelta P$$

Where R is the resistance, R_0 is the initial resistance and P is the pressure [6], [14].

Since most Piezoresistive pressure sensors developed address electronic skin applications, there is a need for enhancing as much as possible the sensitivity of these sensors. Common strategies for enhancing pressure sensitivity consists of modifying the structural surface of the electrodes by incorporating patterned microstructures, such as pyramids and micro-pillars, to provide large changes in contact resistance upon application of varying intensities of pressure [6], [7].

2.2.5.3 Advantages and Disadvantages of Piezoresistive sensors

To summarize, Piezoresistive Sensors are characterized by a simple design that makes them simpler and cheaper to fabricate than other sensors for a wide range of applications, also allowing for low power consumption in the end devices. The high sensitivity and wide detection range allows for a broad usage with varying scope. Finally, their robustness and durability make them suitable candidates for the integration within wearable devices to monitor occupational safety in harsh environments such as construction sites and factories.

On the other hand, some of the main limitations which are still under study are represented by their poor stability, temperature-dependence, and low response time. Furthermore, they require a power supply to operate, which can limit their scope if not designed properly or in synergy with other technologies that allow energy harvesting from the environment.

Many cutting-edge Machine Learning assisted electromechanical sensing systems take advantage of the qualities of piezoresistive sensors, with applications in health care, gesture and gait recognition and tactile perception for e-skin [10]. In the following chapter we will focus on how some of these sensors are fabricated and integrated into textiles for usage in the field of occupation safety.

2.3 Key sensor parameters

As with all sensing technologies, the range of available materials and fabrication methods for piezoresistive sensors that are explored in the literature are quite extensive. It becomes important to define the key parameters that are used to understand a sensor's capabilities and limitations, especially when investigating technologies that need specific characteristics for the creation of smart garments in non-controlled environments. These parameters also serve a purpose in understanding which tradeoffs and design requirements are needed to implement these technologies into full-fledged electronic devices. The most important parameters are the following:

2.3.1 Sensitivity (S)

Sensitivity or Gain is a parameter that measures the accuracy and efficiency of sensors and is defined by the rate of change between the measured output regarding the measured input [7]. Since the method for defining sensitivity depends on the type of sensing mechanisms employed and the type of quantity being measured [14], for pressure piezoresistive sensors it is useful to define it by the rate of change in the output signal (X), the resistivity, with respect to the imposed stress (P), be it tensile or compression [7].

$$S = dX / dP$$

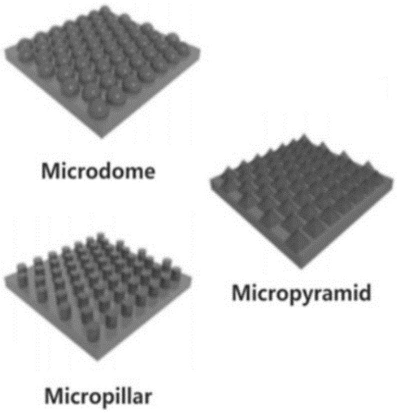

Figure 2 - Example of different microstructures [17]

Sensitivity values obtained depend on the active materials used for the sensors and sensing mechanism type, but also on the physical structure of the sensor itself and the input values of applied strain/pressure. Throughout the years, many fabrication strategies have been developed with the sole purpose of improving the sensitivity of the devices. One example of such strategies for flexible piezoresistive sensors, is the adding of microstructures on the elastomer surface, like arrays of columns or cylinders. The specifically designed surface provides a larger change in contact area with smaller degrees of pressure, thus greatly improving overall sensitivity of the sensor [14].

2.3.2 Gauge Factor (GF)

The Gauge Factor is the equivalent to the sensitivity parameter but applied to the case of strain measuring sensors. The GF value is dimensionless, and is regulated by the following law:

$$GF = (\Delta R / R_0) / \varepsilon$$

Where ΔR is the resistance variation, R is the resistance value under deformation, and R_0 is the resistance initial value, while ε is the applied strain on the sensor. The Gauge Factor values usually vary between 2 and >100, based on the sensor structure and materials [7], [14], [15].

2.3.3 Range of detection (RoD)

The RoD is the range between the lowest and highest amount of stress that the sensor can detect. [7], [14] Usually instead of RoD, the Limit of Detection (LoD) parameter is of more common usage in the literature. But given the wide range of stress values that human motion can impose on sensors, from the lowest measurable mechanical stress coming from pulsatile blood passing through veins [6] to the highest being for example that of large joint movements [14], it is more reasonable to consider the RoD parameter when evaluating piezoresistive sensors, as reported in several reviews on wearable sensors like [7] and [14].

In general, there is an inverse relationship between sensitivity values and RoD, meaning that a highly sensitive sensor will usually have a limited RoD [14], [16].

2.3.4 Linearity

This parameter is defined by the percentage of deviation of the output signal from the defined calibration curve, and is a significant measure of the stability of the signal over an application range [7]. It is important for the sensor to show a linear relationship between the input and the output, especially to ease following data processing from the acquiring devices. By using linear regression, the value of the coefficient of determination is calculated. If the value of this coefficient is large, the sensors performance it is said to be linear [14].

Usually, it is difficult to obtain high sensitivity over a broad linearity range. And since most flexible sensors have a high chance of having non-homogeneous deformations in parts of their structure, that can also lead to non-linearity of the output. This leads to various tradeoffs between high-sensitivity, high-linearity, and stretchability, and cases where, for example, the sensor can show linear behavior in multiple sensing ranges with low stretchability or vice versa [14].

2.3.5 Stretchability (E)

Stretchability is an important factor in wearable sensors and is defined by the elastic modulus (Young's modulus) of the sensor in the tensile test. In the linear region of the curve, it is defined by:

$$E = d\sigma /\, d\varepsilon$$

σ is the applied stress and ε is the corresponding strain. Usually however, stretchability is depicted simply by stating the maximum strain a sensor can tolerate without failure in function.

This parameter depends on the type of materials used for the sensor's construction and the interaction between them, as well as the fabrication process and filler materials used. Typically, making a device out of very thin or ultra-thin sheets of material grants it flexibility, but that often does not translate into stretchability [14].

As mentioned before, highly stretchable strain sensors generally enjoy very low sensitivity (low GF) and show a very nonlinear behavior [7]. The incongruous relationship between stretchability and sensitivity caused by the different operating strain ranges has been proven through the literature, with high stretchability requiring the sensors to remain functional under large strains, while high sensitivity requiring the sensor to detect structural changes under the tiniest of strains [14], [15].

In the case of skin-mounted strain sensors, if the elastic module is close to that of the epidermal layer, that would lead to a stronger sense of comfort in the user, which is also important to help with user compliance in the usage of the device.

2.3.6 Hysteresis

Hysteresis is a parameter that grants information about the difference in performance of the sensor in output for increasing and then decreasing input values. It also influences measurement inaccuracy, manifested as the variation between loading curve and unloading curve [17]. Since flexible sensors are subjected to mechanical deformations, too much physical stress can not only affect the shape of the sensor but also its electrical characteristics.

Resistive flexible sensors based on polymer composite materials are more inclined to suffer from hysteresis due to their viscoelastic nature and the inability of its internal conductive network to fully recover after rearranging under stress [14], [17]. That is not the case for all resistive sensors though, as some developments have seen low degrees of hysteresis, like for example a pressure sensor obtained from silver nanowires embedded in a PDMS matrix reported in [14].

2.3.7 Durability

When dealing with devices that undergo mechanical stress, device failure is inevitable. Even for highly stretchable sensors this factor must be taken into consideration when evaluating the sensor's adequacy for the desired applications. One way of measuring durability for sensors in literature is averaging the number of cycles before the sensor undergoes failure in function [6].

Important factors that influence durability and are usually experienced by wearable flexible sensors, range from normal wear and tear and various mechanical stresses to all kinds of environmental conditions, like contact with skin fluids, or withstanding weather situations [14]. Degradation of performance can also occur during washing of the garments, often resulting in lower rates of reproducibility and accuracy. Encapsulating the device with an insulating layer, or coating with silicone rubbers or PDMS the surface of fiber-based electronics, are some suggested methods for improving resilience to environmental conditions and to improve long-term stability of the devices, as well as allowing them to be washable like normal fibers [18], [19]. One example of this technique is the commercial smart jacket "Jacquard" resulted from the partnership between Google and Levi. This washable jacket has textile switches on the sleeve made by braiding copper wires coated with PU which can be used to control a smartphone [19].

As reported by Sharma et al., it doesn't seem that a standard cycle number defined for sensors is agreed upon in literature, but it is generally calculated for 5,000 cycles.

2.3.8 Response time

Response time intuitively is the time required for a sensor to respond to the external stimulus, reaching a stable, distinguishable output. From a quantitative point of view, it corresponds to the time required from the sensor output signal to go from no response to a specific percentage (usually 90 or 95%) of the maximum step change induced by external stimulus. For real-time monitoring and especially for monitoring of human activities, the shorter the response time of the sensor, the more acceptable it is [7].

2.3.9 Power consumption

Power consumption is an important factor in sensors for wearable applications. A high-power consumption can reduce maximum operating times and comfortability of the device due to the need for more bulky setups necessary to accommodate larger power supplies. A high-power need can even reduce user safety, as most of the battery technologies as of today cannot sustain significant mechanical stress or puncture without risking explosions, burns and chemical exposure.

The performance of low-power applications is dependent on the capability of the power supply to be not only reasonably small, flexible and durable, but also efficient enough to operate the sensor, the processing systems, and the data handling systems (be it wireless transmission or local storage) [15]. Numerous energy storage and harvesting technologies have been developed for wearable systems, but finding a viable power source still presents a challenge. On one hand, there are numerous efforts in the development of stretchable or fabric-based batteries and supercapacitors, but making them simultaneously durable, safe, flexible and with a sufficiently high energy density remains a difficult endeavor [8]. On the other hand, self-powered energy harvesting systems reduce the need for large energy-storage solutions, but to maximize their efficiency they need to have a high enough energy capacity, and an intimate contact with the skin, or at least the capability of being modeled to its shape [15].

Having a low power consumption for a sensor can immensely benefit the designing of safe and comfortable portable devices, especially when considering high-risk or harmful environments. And it becomes even more important for applicability in mobile and hard-to access devices, like in locomotion surveillance [7].

2.3.10 Other important parameters and final considerations

Some other important parameters that define sensors and need mentioning include:

- *Repeatability*, a parameter that identifies variations that can occur when conditions for the measurement are constant and done withing a short period of time.
- *Resolution*, which is the ability to measure and detect and faithfully indicate small changes in the characteristic of the measurement result.
- *Offset* of the sensor output signal, which can have its origin values lower or higher than the ideal output.

The above parameters and most of the previously mentioned ones can be extracted and highlighted from the characteristic curve that is obtained from measuring sensor’s response to an input. If a sensor is found lacking in some departments, conditioning, and processing the sensor's output signal can improve their shortcomings, to some degree.

3.1.10.1 Biocompatibility

Beyond the electrical and physical parameters that define sensors, in the case of wearable devices it is also important to factor in biocompatibility. Using materials that are biocompatible means ensuring that the devices employed can cause no harm to users by intent or accident, but when it comes to humans its meaning is also expanded to that of comfortability [15]. So it becomes important that the devised wearables are designed to be light weight and allow for breathability, flexibility, and ease of use [20]. It becomes especially important when lack of breathability can lead to adverse and lasting physiological effects due to the blocking of airflow around the skin causing irritation and inflammation [19]. Compared with polymers, textiles satisfy the criteria, having also high mechanical strength besides the expected comfort [10]. Biocompatibility can also mean having the possibility of creating bioabsorbable self-powered electronic devices which employ materials that can dissolve completely in the body without leaving toxic residue. Lim et al. presents a general classification with examples of researched bioabsorbable materials, which range from metals and inorganics to natural derived and as well as synthetic polymers. These materials form the basis for each contributing part that can constitute the sensor, be it electrode, substrate or any other functional layer [15].

3.1.10.2 Scalability

A final characteristic that is not easily defined and needs consideration is the scalability of the sensor's technology and its production cost. Large-scalability and good cost efficiency of the production process are critical in the successful adoption of commercial applications. This also means that the technologies employed must be suitable for high throughput production processes and possess the mechanical properties needed for textile processing, while also enduring all the typical mechanical and chemical stresses that are normal during the lifetime of conventional textiles [19]. As an example, the previously mentioned project Jacquard had good resilience to rain, to washing and regular wear, while also using low-cost materials. But the end cost of integration and fabrication resulted in the high product price of US$ 350 at its launch [21], which made it impractical for the average smartphone user, which was the intended product audience. It then becomes even more impractical if it is a garment intended for work-safety applications and physical-demanding environments.

Chapter 3 - Piezoresistive sensors for textile integration

There are numerous sensors that are good candidates for textile integration and with characteristics advantageous for work safety wearables. But unlike other sensor technologies, piezoresistive flexible sensors offer inherent advantages such as flexibility and adaptability to various surfaces and environments as well as having simple working mechanisms that allow for rapid integration, and generally excellent durability. Their versatility, combined with the potential for cost-effective manufacturing and scalable deployment, positions piezoresistive flexible sensors as a compelling choice for enhancing safety measures in occupational settings.

3.1 General structure of flexible sensors

Piezoresistive sensors are made with a variety of materials and techniques, making them often very difficult to define and classify. From a fabrication point of view, a possible and valuable strategy to deep their characteristics may take into consideration the principal element from which they are composed: substrate, conductive layer, sensing layer and finally protective layer. Each of these elements will be fully described in the following paragraphs.

3.1.1 Substrate and materials

The substrate is the core, or base of the sensor, and it's a layer composed of a flexible and deformable medium over which the subsequent layers are often integrated on. The main role of the substrate is to provide a support or a foundation on which the active materials are then integrated to enable sensing [14].

This layer can be in the form of a film or a thread, and the common choices for the material include PDMS, which is a commercially available silicone elastomer with high stretchability (up to 1,000%) and non-toxic, which are some of the reasons that make it frequently used in wearable solutions. Other used materials from the silicone elastomer category are the commercially known Ecoflex, Sylgard, Dragon Skin, and Silbione, all of which are also biocompatible and have a maximum stretchability up to 900%. Polyimide (PI) is another material frequently used for its capacity to maintain flexibility at high temperatures and in acidic/alkaline environments. Other common polymers for the substrate are PU, polyethylene terephthalate (PET), and polyvinyl acetate (PVA). Some natural materials and textiles are often explored in the literature for their biocompatibility and flexibility, like for example cellulose paper, silk and cotton. [14], [17], [22].

Durability and elasticity are key factors in the choice of the materials, as well as good compromises for the key parameters of the sensors that are mentioned in the previous chapter.

3.1.2 Conductive layer: the electrodes

The conductive layer, often designed in the shape of electrodes, is responsible for transporting the electrical signals to and from the piezoresistive materials. In textile integration, oftentimes this layer is seen merged with the sensing layer, especially in one dimensional applications, like for example the case of strain sensing fabrics [18].This layer usually consists of highly conductive materials, such as liquid metal, silver, carbon black (CB) composites, polyacrylonitrile (PAN) and so on [23].

3.1.3 Sensing Layer: the piezoresistive material

The sensing layer, often applied as a thin film or coating on the substrate, has the piezoresistive qualities that allow the sensor to have an electrical resistance response to mechanical deformation.

Common materials seen in flexible sensors for the active elements are:

- Carbon nanomaterials, including graphite, carbon nanotubes (CNT), graphene (one atom thick sheets of carbon atoms), but also composites like MXenes, which are popular in the fabrication of flexible pressure sensors. These materials possess excellent electrical conductivity and mechanical properties [7], [10], [14], [22].
- Metals in the forms of nanowires (NWs), nanoparticles (NPs), stretchable configurations or liquid states (at room temperature), that exhibit excellent electrical conductivity. NWs and NPs, together with conductive ink, are usually used to prepare piezoresistive composites [7], [10], [14], [22].
- Conductive polymers, because of their shared similarities with insulated substrate polymers. Some of the most common sensing materials, used for their thermal stability, high transparency and tunable conductivity are PEDOT-based polymers, poly(3,4-ethylenedioxythiophene)-polystyrene sulfonate (PEDOT: PSS) inks used on fabrics and cellulose substrates, PVDF [7], [14], [22].

One important thing to note is that because of how flexible sensors are generally made, oftentimes the same materials used for the sensing layer can be used in the fabrication of the conductive one.

3.1.4 Protective layer or Encapsulation

The protective layer has the purpose of shielding the underlying sensor from external factors but can also serve to protect the user from the sensor itself and the electronics. Thus, flexible, and biocompatible materials are needed, that can stay in direct contact with the skin and survive the stresses that the sensor will be subject to. Some common flexible and cleaning-resistant materials used for the fabrication of the encapsulation are PDMS and poly(styrene-b-butadiene-b-styrene) (SBS) [23].

3.1.5 Other considerations for flexible piezoresistive sensors

While the four layers mentioned above can define a sufficiently correct representation of the structure of a flexible piezoresistive sensor, this clear subdivision is generally not how they are described. Striving to maximize the key parameters of sensors while ensuring flexibility and biocompatibility means that their structure can vary wildly in the literature, and some layers can even be merged. This is often the case when considering single layered sensors. In this case, a single layer of porous, flexible, and insulating matrix is filled with traces of other conductive materials, called fillers, which allow for a single piezoresistive device. Other cases, for example, involve the assimilation of a conductive material in the form of an ink, that is absorbed by the textile substrate of the cloth, with the piezoresistive layer being separate from these two. The most common explanations for the transduction mechanisms of these materials include considerations on the change of the geometrical structure, change of the intrinsic piezoresistive effect, the structural effect, which considers the crystal structural changes in the material, and the tunnelling effect after initial separation between the conductive materials inside, and microcrack propagation [7], [22].

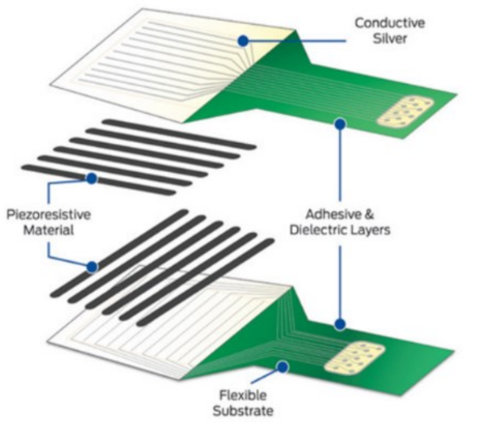

Figure 3 - example of 2D piezoresistive sensor layer organization [17]

It is also important to consider that the use of fillers and the emergence of fibrous sensors can make the classification and distinction of the different layers for the structure of these technologies vaguer than one might expect.

Together with all the different mechanisms and techniques attempted throughout the years to enhance the different features and parameters, most sensors don't see a distinct classification of their structure in the literature. They are simply described by the active materials employed in their construction and the fabrication process used to obtain them.

Finally, the sensors are also seen in the form of arrays of sensors. This is especially true for pressure sensing applications where it is necessary to distinguish fine details and patterns with the sensor, as well as the exact position where the pressure is on the device.

3.2 Piezoresistive strain sensors for textile integration

The following pages will explore some intriguing recent implementations of piezoresistive strain sensors that hold great promise for seamless integration into textiles.

3.2.1 Washable C-PBT strain sensing thread

The single thread strain sensor proposed by Sadeqi et al. in 2018 [18] was designed to maintain performance after multiple washing cycles with harsh detergents, and to have a cost-effective fabrication method.

Made by coating carbon resistive ink on a PBT puffy thread and cured in PDMS, this thread-based sensor was proven of easy and low-cost fabrication and has demonstrated linear resistance values increases under 40% strain.

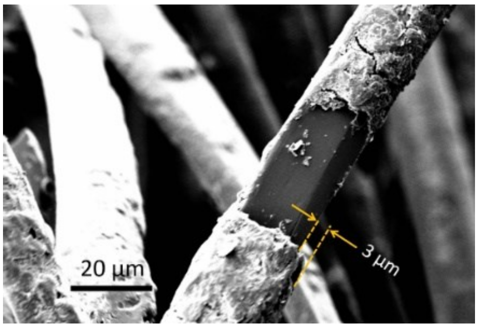

Figure 4 – SEM image of the scratched final thread, showing the encapsulating layer thickness [18]

3.2.1.1 Materials and fabrication

For the fabrication process of this sensor, a new method was proposed by the authors to enhance the resistance to rough handling, environmental degradation, and repeated textile maintenance. Current approaches to the fabrication involve photolithographic patterning of textiles with smart materials through screen printing or ink jet printing, but the underlying fabric cannot withstand rough environments.

To fabricate the sensor, the threads were harvested from PBT bandages. The thread is composed of very thin PBT fiber with helical coiled up shapes that confer elastic properties. By dip-coating the thread in C-200 Carbon Resistive Ink, the coated fibers gain piezoresistive properties that allowed for the measuring of strain changes along the thread.

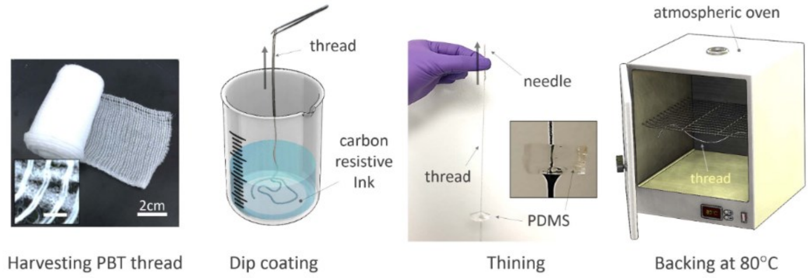

Figure 5 - Fabrication process for the thread-based, washable strain sensor [18]

The newly obtained carbon coated PBT thread (C-PBT) by itself is not washable and when immersed in cleaning solutions can have the carbon particles fall off. To protect the thread, they coated it with PDMS, since it's a known skin-compatible and hydrophobic polymer that can shield the thread without compromising its properties. The coating process itself consisted of simply passing the thread through a cured PDMS membrane 5mm thick by using a needle. During the encapsulation the fibers are elongated and fully stretched, a process not done during the initial coating of the PBT string. The PDMS encapsulation also has the benefit of improving the sensor's stretchability with its own inherent elasticity.

After this, the thread is left in an atmospheric oven at 80°C for 30 minutes to be cured and is then attached at both ends with aluminum tape to obtain electrical connections to the sensor.

3.2.1.2 Performance

To ascertain the sensor's performance with washing cycles, the authors experimented with submerging the thread in a beaker containing different detergents and using a magnetic stir bar to subject it to 1100 rpm rotation forces. Besides Acetone which dissolved the thread, they reported a good degree of success with other solvents and detergents, with the thread showing good overall immunity and washability.

In the end, the thread-based sensor showed low hysteresis up to 37% strain, with 1,000 cycles of durability at 1Hz and less than 5% drift. The average gauge factor was of about 2.5 and did not show significant changes across its working range.

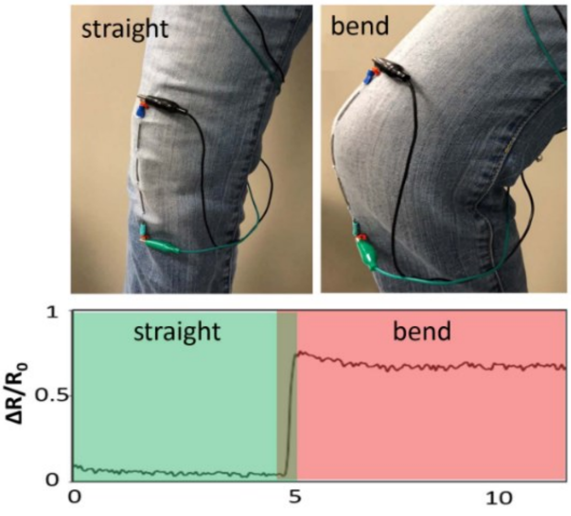

Figure 6 - Demonstration of the response of the sensor [18]

The authors suggested for this sensor applications in human motion and physiological monitoring in real time. While by itself the characteristics of the thread-based sensor in question are not groundbreaking, the form factor, which allows for the sensor to be seamlessly sewn into clothing, and durability it exhibits, show promise for future developments of thread-based sensors for work safety applications.

3.2.2 Stretchable CNT strain sensors

The promising sensor introduced by Suzuki et al. in 2016 [24] could detect strains exceeding 100%, with high linear resistance variation relative to the strain, high GF, rapid responses to large strains and excellent general robustness. The manufacturing process of these sensors are suitable for mass production and with a wide range of shapes, making them useful for many cost-effective applications, like the ones considered for this thesis.

3.2.2.1 Materials and fabrication

The sensor was manufactured by placing a CNT sheet on a flat and smooth substrate, in a direction that is parallel to the stretching direction intended for the device, and then impregnating the sheet with an elastomeric resin.

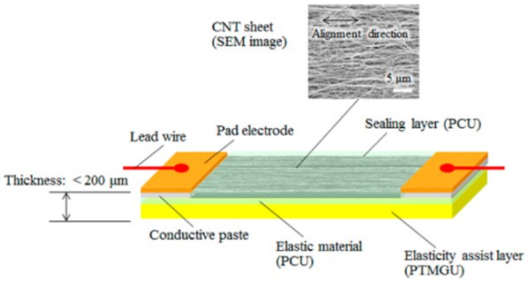

Figure 7 - Structure of the proposed CNT strain sensor [24]

The CNT sheet was produced by stacking a multi-walled carbon nanotube (MWCNT) web on a rotating drum and cutting one end to flatten it. The sheet has an average between 8 and 12 web layers that were drawn at about 10mm/sec. By adjusting the number of layers, the resistance of each CNT sheet could be adjusted. The control of the resistance of the CNT sheet and of the sensor’s resistance allows for high reproducibility of the sensor device.

After separating the CNT sheet from the drum, it is combined with an elastomer resin layer that has low elasticity and low loss properties. Polycarbonate-urethane resin (PCU) was chosen for its ease of bonding, durability, hydrolysis, and chemical resistance. The resin was then applied with a spin coater to a thickness of several dozen micrometers. And to stabilize the behavior of the device during contraction, an elasticity assisting layer has been added to the elastomer resin, composed of polytetramethylene ether glycol-urethan (PTMGU).

Finally, lead wires were attached with conductive paste to the ends of the sensor, to allow connectivity to the sensor.

3.2.2.2 Performance

Besides an initial hysteresis behavior during the first stretch of the sensor, where the resistance is not restored to the initial values, the proposed sensor shows optimal hysteresis in all successive cycles. The stretchable sensor can be stretched up to 200% and show a sensing delay of less than 15ms, with high sensitivity proven by gauge factor values greater than 10. Furthermore, the study states that 20°C repetition durability of over 180,000 cycles was observed. These characteristics make this sensor ideal for textile-based, real-time wearable applications of human body motion-sensing. An example of these applications is the prototype data glove proposed by the study, which was evaluated by acquiring test measurements of finger motions during a piano performance. The ability to integrate the sensor in breathable and flexible fabrics allowed for prolonged and comfortable use of the glove. The authors also state that the subtle finger movements were accurately captured in real time for both performances of amateur and professional pianists that were employed for the testing of the prototype. Other prototypes were also proposed and developed, such as smart sleave motion sensing garments that make use of the sensor's capabilities.

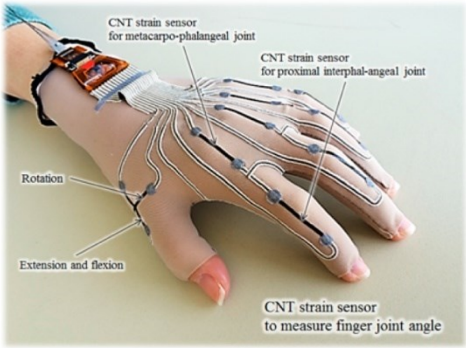

Figure 8 - Application example of a Data glove made with CNT strain sensors [24]

3.2.3 Wearable strain sensor based on carbonized melamine sponges

In another study from 2017, Fang et al. [25] developed a fragmented carbon melanin sponge (FCMS) sensor with important characteristics for wearable applications. Improving upon the already existing proposed design of carbonized melamine sponges, this implementation managed to expand the limited strain sensing range and relatively low GF, resulting in a sensor that is adequate for wearable applications, and more durable. Althrough 3D carbon sponges are commonly seen used without structural deformation in the litterature, this sensor is an example of using fragments of the sponge's three-dimensional structure in a bidimensional final sensor.

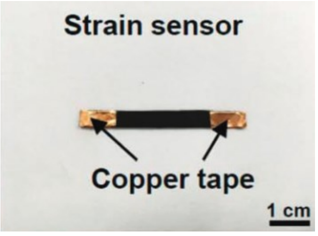

Figure 9 - FCMS sensor [25]

3.2.3.1 Materials and fabrication

Melamine Sponge (MS) is a material that sees large usage in the production of kitchen utensils and as a construction material. It is made of an interconnected network of formaldehyde-melamine resin. It's often employed as a supercapacitor electrode because of its high electrical conductivity and as an oil and organic wastes absorber thanks to its porosity and super hydrophobicity.

After rinsing a commercially available MS in ethanol, to remove impurities, it was dried at 70°C for 4 hours and then prepared in a vacuum furnace for the process of carbonization. This process allows for the conversion of the MS matter into carbon, which was obtained by vacuuming the furnace to a pressure of circa 2 Pa and heated at a temperature of 800°C for one hour.

After cooling down the now obtained carbonized MS (CMS), it has been ground powdered by using a mortar and then dispersed and ultrasonicated into a solution of deionized water with sodium-dodecyl-benzenesulfonate. The obtained solution with the fragmented CMS (FCMS) was then vacuum filtered after a rest period of one hour, onto a piece of cellulose ester (MCE) membrane, to form a FCMS film. A 1:10 weight ratio of PDMS is poured onto the film, followed by a curing process at 60°C for 2 hours. The MCE membrane is then removed via acetone, and the remaining FCMS/PDMS film is cut into the final sensor shape with added copper tapes at the end. The copper tape is attached using carbon grease to enhance chemical conduction between collectors and sensors. Lastly, a small amount of PDMS is used to seal them.

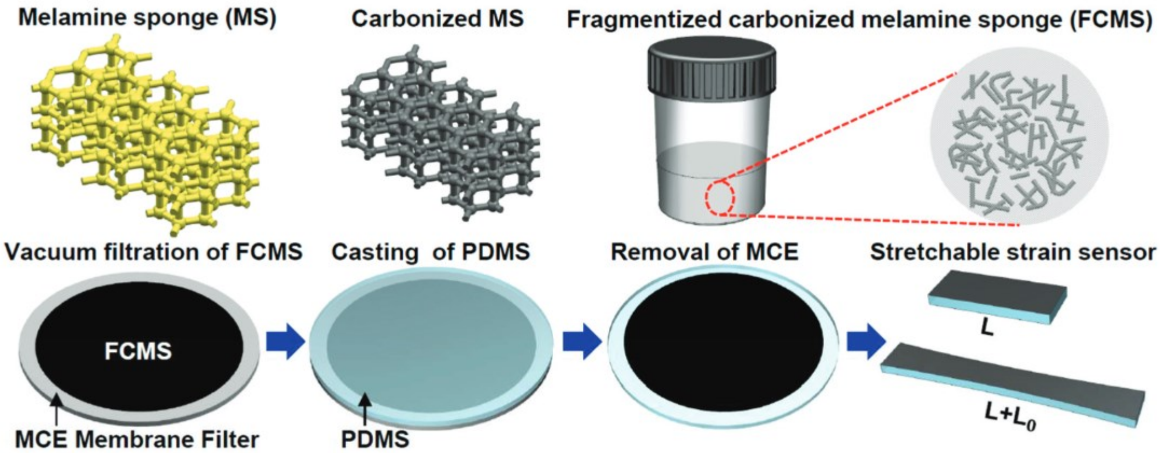

Figure 10 - Fabrication process of the FCMS based sensor [25]

3.2.3.3 Performance

The FCMS-based sensor developed in the study shows a high sensitivity and good sensing range. The limit of detection was shown to be about 0.01%, with GF of 5.0 at strain $\varepsilon < 40\%$ and 18.7 at strain higher than 40%. After 10,000 stretching-releasing cycles with strain under 20%, the device maintained its performance with no noticeable detachment of the FCMS from the PDMS substrate. At 80% strain, the device can be subjected to 10 cycles without issues, suggesting a high overall durability of the device.

Applications suggested by the authors for the high sensitivity and large strain sensing range of the sensor include the detection of large-strain human body motions such as bending of fingers and wrists, joint movements but also of subtle-strain human motion such as artery pressure waveforms, phonation, and respiration. Some tests were performed in this sense to prove the potential of the device in providing health-related information, with good overall results. Although the sensor was not tested for harsh environments, initial assessments show little influence in the performance of measurement with different levels of humidity, but more in-depth testing is suggested before adopting it for high stress environments. Together with a cost-effective and scalable process of fabrication, the design of this sensor also shows promise for wearable applications in human safety monitoring.

3.3 Piezoresistive pressure sensors for textile integration

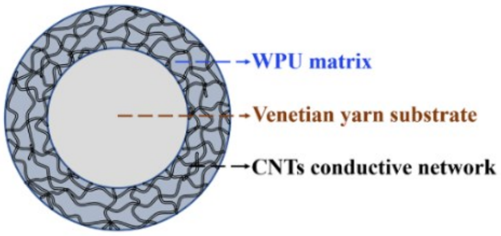

Figure 11 - Schematic cross section of the conductive Venetian yarn [20]

Pressure sensors developed for human motion monitoring are designed to sense compression stresses in a wide range of values, from subtle mechanical stimuli that produce very small strains on the device as well as very large ones, allowing applications like for example electronics skin. Often, the mechanisms used to detect pressure are not very different than those of strain sensors, with the main difference being that in the design choices sensibility at low amounts of strain is favored over assuring great stretchability of the device. Generally, conventional piezoresistive pressure sensors struggle to achieve high sensitivity and a wide pressure range [16]

3.3.1 All textile-based pressure sensor

An interesting example of pressure piezoresistive sensors is offered by the completely textile-based sensor developed by Liu et al. in 2023 [20]. By employing Venetian fabric that has been impregnated with polyurethan/carbon nanotubes, they propose a low-cost, scalable approach for the fabrication of a mechanically robust pressure sensor that is composed entirely of textiles.

3.3.1.1 Materials and fabrication

The substrate for this sensor was composed of polyester fabrics. The flexible interdigital electrodes proposed were obtained by screen-printing an elastic conductive carbon ink (CH-8 (MOD2)) on the substrate via a screen mesh. After extruding the ink onto the bottom fabric, the polyester fabric was put in an oven at 100°C for 20 minutes to cure the printed ink.

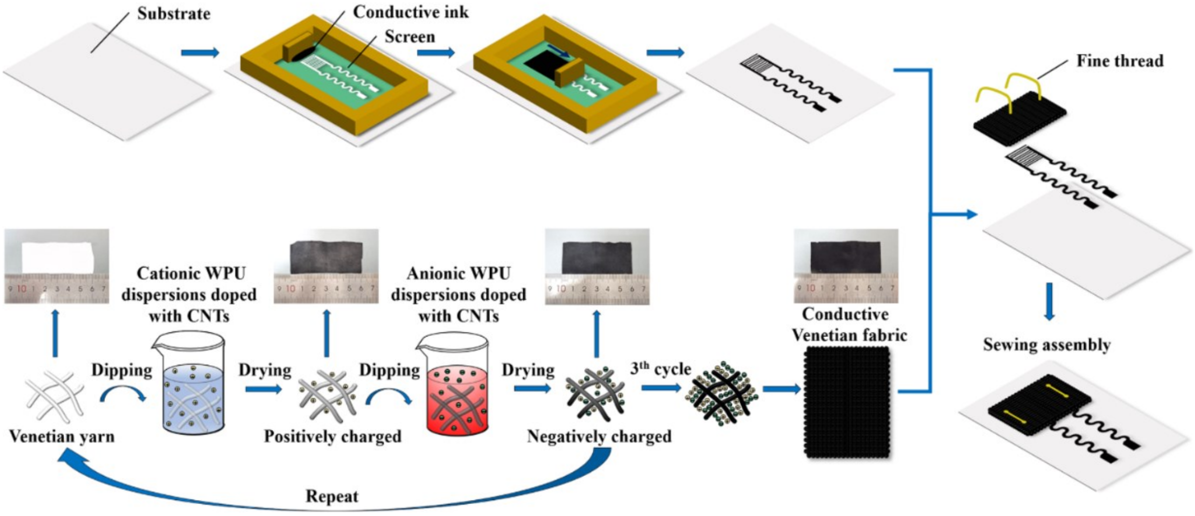

Figure 12 - Fabrication process of the all-textile sensor (Liu et al. 2023)

The sensing piezoresistive layer, on the other hand, was made from Venetian fabrics (90% Polyester and 10% spandex) by using a layer-by-layer (LBL) assembly method. The LBL cycle assembly consists of five different coatings at a temperature of 50°C for 15 minutes. The coatings were solutions of cationic and anionic waterborne polyurethane (WPU) dispersions doped with CNTs obtained from a conductive CNT paste with a mass fraction of 6.3 wt%. After three to five cycles, a Venetian fabric with conductive resistance was obtained.

The newly achieved sensing layer was then sewn on the polyester substrate in correspondence with the flexible electrodes. For the testing of this sensor the authors covered the inside part of the polyester substrate with insulating fabric to remove any interference in measurements from the contact with human skin.

3.3.1.2 Performance

From the tests done by the authors, they found that an increase in LDL assembly cycles correlates to a higher sensitivity of the fabrics. They also discovered that the limit of the detection of the proposed sensor corresponds to a pressure of about 38 Pa, while exhibiting a fast response time of 32ms and a recovery time of about 4ms. These characteristics were attributed to the porous high elastic structure of the Venetian fabric and are desirable for sensors used for real time monitoring of human motion. Further tests on durability with loading and unloading were done on the sensors for 10,000 cycles with negligible change of the response curves during the whole process, confirming repeatability robustness and reliability for the long-term usage. The textile-based sensor also exhibits good washability and water resistance and can work well in wet conditions or after repeated cycles of washing. The chosen substrate material is also known for providing comfort during long term usage.

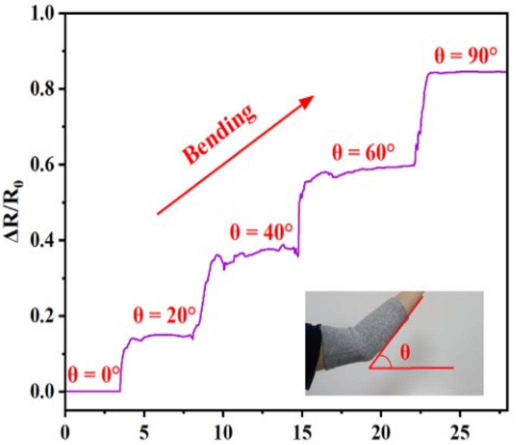

Figure 13 - Response signals of the elbow pad prototype to different bending angles [20]

While this proposed sensor design is suggested mainly for pressure sensing applications like artificial skin, it can also be used for strain sensing applications like joint and finger motion monitoring thanks to its sufficiently good elasticity and durability. Two very interesting applications of this design proposed and tested by the authors are a working prototype of integrated elbow-pad used for monitoring bending angles, and a smart glove capable of sensing the bending of distinct fingers and their applied pressure, with good performances. Overall, these sensors show a lot of promise in human motion monitoring and can be employed for sensing a wide range of movements useful for work safety applications.

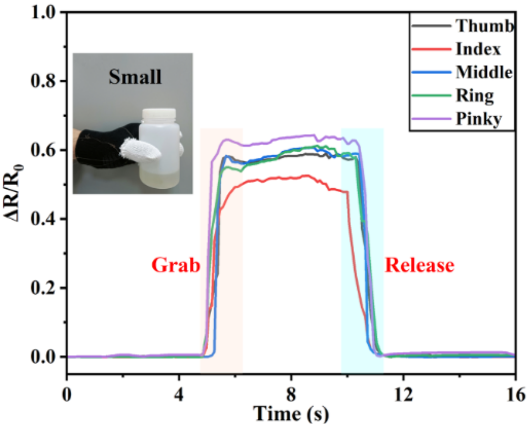

Figure 14 - Realtime sensor response to the gripping of a small object [20]

3.3.2 Stretchable electronic fabric artificial skin

Another interesting implementation of a piezoresistive pressure sensor is provided by Ge et al. in their research from 2016 [26]. The authors managed to create a low-cost electronic fabric composed from a stretchable sensor array which can map and quantify stresses induced by pressure, lateral strain, and flexion.

3.3.2.1 Materials and fabrication

The fabric developed by the authors was designed to mimic the sensitivity of human skin. The design consists of conductive elastic threads, coated with piezoresistive rubber, and weaved in a stretchable electronic fabric.

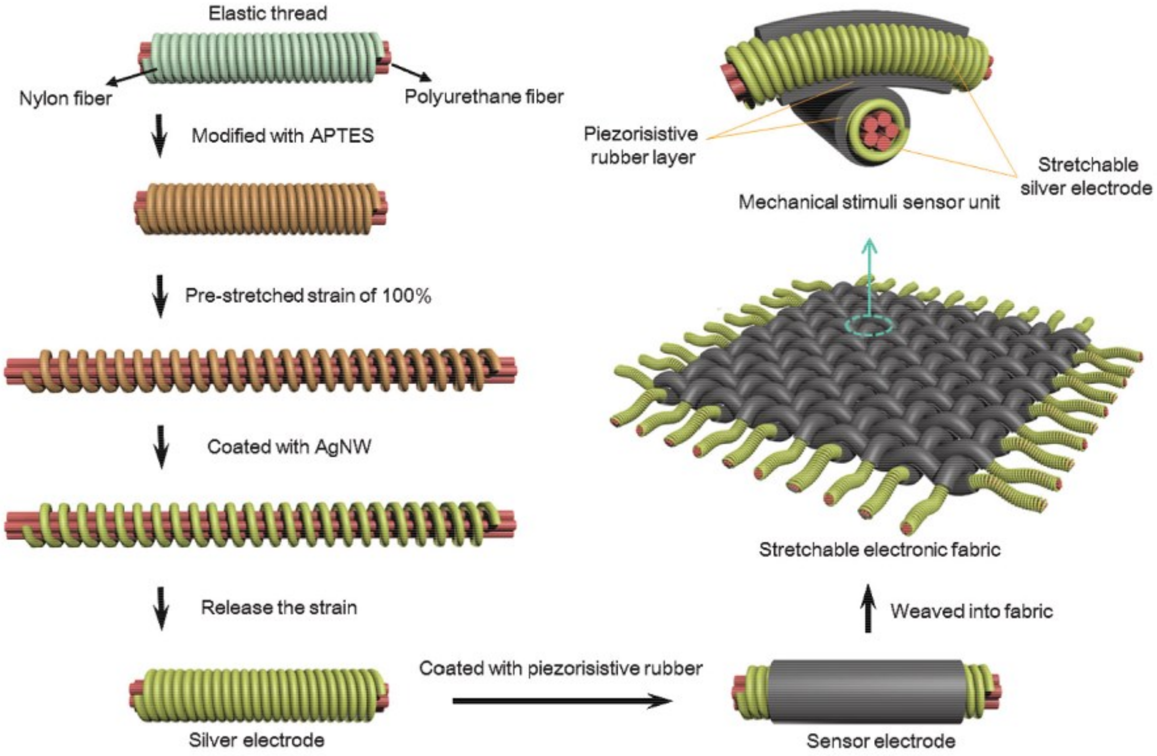

Figure 15 - Steps done for the fabrication of the sensor [26]

The commercially available threads with inner PU fibers at the core and nylon fiber twisted around them, were first treated with 3-triethoxysilylpropylamine (APTES), and then stretched to 100% tensile strain to be coated with an AgNW dispersion through a dip-coating process. Through this process and after releasing the thread from the strain, they achieved a helical AgNWs network around the fabric with a high electric conductivity that was able to endure tensile deformation and served as the conductive layer. The thread is then coated with a mixture of PDMS and carbon black. Both the silver nanowire network and rubber coating grant the sensor remarkable stretchability and conductivity. The resulting composite fibers now function as the sensor electrodes. The sensor is then obtained through the weaving of these threads together in a large-area fabric. The crossing points between the intertwined fibers act as individual sensor units that are capable of detecting changes in pressure, strain, and flexion.

3.3.2.2 Performance

The pressure sensing sensor obtained by this process is reportedly capable of enduring over 100,000 cycles of mechanical deformation without significant loss of function. The device also exhibits little hysteresis to input pressure and can maintain more than 50% of its sensitivity even after being subjected to its maximum tensile strain.

The general stretchability, robust mechanical properties, and reliability under constant usage makes the suggested technology very promising for wearable applications. The low-cost of the materials and fabrication justify usage in consumer-grade mass-produced wearable technologies like those used for human motion monitoring in work safety. But further considerations in the device's resilience to water and textile maintenance must be made, that the paper does not address. The authors envisioned integration of this technology for humanoid robots and artificial skin applications, as well implementation in biomedical prostheses, that could offer users more precise control and feedback. The sensor's characteristics also make it suitable for other wearable health monitoring applications.

3.4 Sensor conditioning, signal acquisition and processing

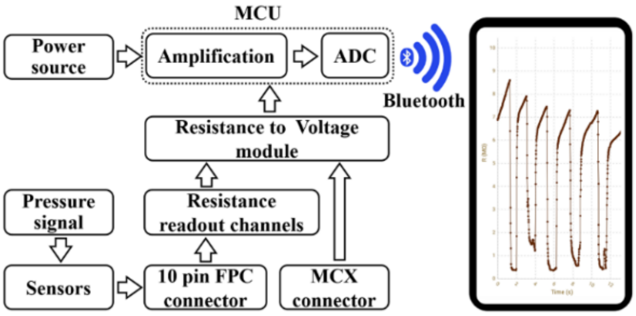

Figure 16 – General signal conditioning and transmission chain for the all-textile sensor [20]

After the sensor has converted the real-world physical input into an electrically measurable signal, the information must be conditioned for the subsequent digital conversion and processing of the information. This is generally done by a data acquisition system (DAQ). In the case of piezoresistive sensors, as mentioned before, the wanted electrical information is in the form of electrical resistance variation which can be measured in lab settings with a precision digital resistance tester like the one used in [20]. For uncontrolled environments, it is necessary to develop and produce the adequate circuitry that not only measures the resistance changes, but also provides adequate shielding and filtering of disturbances, as well as conversion of the resistance variance into a voltage variation with optimal ranges, which in turn needs to be converted and to digital information. It is then necessary to store, transmit and process the acquired data, which requires another layer of circuitry by itself. Finally, the whole circuitry also needs appropriate power sources to fuel the whole process.

All of this still poses a big challenge, with numerous solutions proposed in the literature in the form of custom and commercially available DAQ hardware that try to fit the needs of wearable applications.

3.4.1 Signal conditioning circuit

The first step in processing the information from the sensor in a DAQ consists in conditioning the sensor with a proper conditioning circuit that enables to obtain the analog signal output (usually a voltage) that varies proportionally with the variation of the target output.

A common transducer design used for resistive sensors is the Wheatstone bridge circuit. When the powered sensor has a change in its resistance R_X values, this gets converted to a change in the measured output tension, based on the formula:

$$V_G = \left(\frac{R_2}{R_1 + R_2} - \frac{R_X}{R_X + R_3}\right) V_{\text{source}}$$

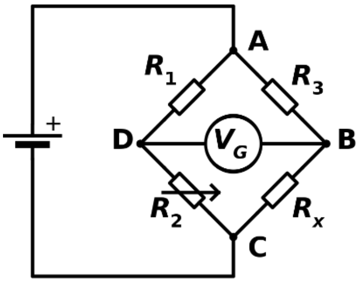

Figure 17 - A Wheatstone bridge circuit diagram (Wikipedia)

The V_G signal can then usually be forwarded in the circuit chain by connecting the output terminals to a differential amplifier, which can isolate the circuitry and act as a signal stabilizer. The variable R_2 resistance acts as a calibration resistor in the bridge circuit and is needed to manually offset to zero the output voltage. This circuit allows for accurate and sensible detections of the resistance values but suffers from a dependence of the output signal on only small variations of the resistance values. A common practice for improving on this aspect consists of using two sensors instead of one, with the second sensor placed instead of R_1, and making sure R_2 and R_3 have matching values. This allows for accurate measurements of R_X regardless of the magnitude of its variation. Numerous commercially available integrated circuit solutions already exist and are readily available for the transduction of resistive sensors, with many features already implemented to insure stability of the output signal.

3.4.2 Acquisition and digital conversion using DAQ

After the transduction of the signal, the signal must be transformed from analog electric information to binary digital data that can be stored, transmitted, and elaborated by a processing unit. This can be easily performed exploiting DAQ that enable the flexible control and digitalization of multiple signals at the same time. For slower multi-channel parallel signals, DAQ designs can make use of a multiplexer technology which serializes the information received from the multiple inputs and sends it as a single output. By switching between the channels at appropriate timings, the multiplexer can have a huge positive impact on the cost and occupied space of the device, eliminating the need to have multiple conditioning and conversion circuitry for every input channel. This though comes with tradeoffs in terms of slower sampling rates and increased latency and may not be advantageous for all wearable applications.

The digital conversion of the signal is then done by an analog-digital converter (ADC), which is one of the key elements of a DAQ and enables the digitalization of the analog signal coming from the conditioning circuit. Through continuous sampling and quantization of the input voltage, the ADC outputs a n-bit binary digital number. The quality of an ADC is defined by its signal-to-noise ratio (SNR), resolution and accuracy, and sampling rate. When custom solutions are developed as part of the DAQ, these parameters must appropriately be accounted for, to ensure that accurate information is acquired and transmitted forward to the processing units.

3.4.3 Data processing

Finally, the information converted by the ADC must be processed. Low-powered solutions with limited space for circuitry usually prefer the direct transmission of the information to portable processing devices or smartphones via low-power communication technologies such as Bluetooth or NFC. If there is no need for real time monitoring, the data can also simply be stored on a storage medium and processed later. But for real-time monitoring solutions it is important to use microprocessors with sufficient processing capacity and low power consumption to ensure timely data processing and long enough operating time of the wearable device. As the use of portable devices for Internet of Things (IoT) applications has become increasingly widespread, a common approach to address the need for compact computational capabilities has been the development of System-on-a-Chip (SoC) solutions. SoCs are integrated circuits that contain all the essential components of a computer, enabling them to efficiently handle data processing, storage, and transmission. In addition to custom-designed systems, commercial solutions like Arduino and similar platforms have gained popularity due to their accessibility and ease of use, making them valuable tools for a wide range of IoT and wearable applications.

For the processing of the data obtained from the sensors, in recent years the wearable industry has made significant strides thanks to machine learning (ML) and deep-learning (DL) algorithms. These algorithms play an increasingly important role in the aiding of scientists with data processing and analysis within wearable intelligent sensing systems. Wearable intelligent sensing systems have seen a sharp increase in the usage of these algorithms which are trained and then applied to real-time sensing systems for gesture and gait recognition, as well as tactile cognition and sensing. Near-sensor computation offers significant advantages, particularly in cases where rapid evaluation and processing of complex sensor data are essential for assessing the user's safety status. Numerous studies have provided comprehensive overviews and evaluations of recent advancements in machine learning-assisted wearable sensing systems, with one notable example being the work conducted by Dai et al. [10].

3.4.5 Power sources

As mentioned in paragraph 2.3.9, power sources for wearable applications still prove to be a significant challenge. Some proposed solutions suggest the usage of other electromechanical technologies to create self-powered devices, like for example the self-powered TENG-based backpack that can harvest vibration from natural human walking [27], or fiber-based organic solar cells suitable for textile weaving mentioned in [19]. Innovations in thermoelectric generators, piezoelectric materials, and energy-efficient circuitry are contributing to a broader selection of opportunities for addressing the power needs of wearable devices. These developments open new avenues for sustainable and self-sufficient wearables.

In parallel with power generation, considerable efforts are being invested in energy storage solutions for wearables. Examples include yarn-based textile batteries and textile supercapacitors, as outlined in [19]. While these textile-based energy storage technologies offer intriguing possibilities, they come with their own set of challenges, including limitations in energy density and manufacturing scalability. However, these challenges also signify opportunities for ongoing research and development to improve their efficiency and practicality.

Concluding, while this provides a general overview of sensor signal acquisition and processing, it is essential to acknowledge that it offers only a simplified glimpse into a vast research domain. Within the extensive field of electronic acquisition and signal processing, numerous intricate aspects including signal amplification, filtering, timing considerations, sample and hold operations, and more, are integral components of this broader research field, each deserving in-depth exploration and study.

Recent developments in sensor technologies, advanced algorithms, and real-world applications highlight the dynamic nature of this research, underscoring the continuous evolution and innovation in wearable electronics.

Chapter 4 - Applications in work safety

Cutting-edge sensors technologies embedded in wearable devices lead the integration of smart technologies into workplace safety applications. By leveraging the capabilities of these technologies, industries can enhance the safety and well-being of their workforce while also significantly reducing the incidence of work-related injuries and improving productivity. From textile-based strain sensors in smart clothing, that monitor body postures, to wearable insoles that detect and analyze gait patterns, these smart safety solutions pave the way for a new era of occupational safety and health management. The following applications serve as examples of what today's technology already makes possible, and hopefully an insight into tomorrow's possibilities.

4.1 Activity and Safety Recognition using Smart Work Shoes for Construction Worksite

The paper published in 2020 by Wang et al. [28] focuses on the development of a wearable textile pressure insole sensor designed to monitor the safety of construction workers in real-time. The study aims to address the high incidence of work-related injuries at construction sites, particularly those caused by falls, tripping, and missteps on stairs. By using the sensor proposed by the paper, the plantar pressure distribution during gait as well as weight-shifting patterns, balance, and posture changes, can be analysed to provide warnings to workers when extreme movements out of the normal range of motion are detected.

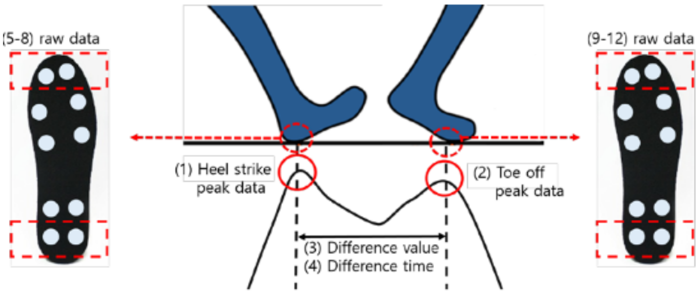

Figure 18 - Insole design [27]

The insole proposed in their paper utilizes 10 capacitive electromechanical sensors and was integrated in a PPE shoe prototype together with a capacitance measurement PCB that has Bluetooth transmission capabilities. The capacitive sensors used in the smart work shoes are textile-based, composed of polyester plated with nickel and copper.

The monitoring for this application was done in real-time and the data was sampled at 100Hz and transmitted to a computer via Bluetooth. The signal processing employed by the authors includes the application of a moving average filter and peak detection using a local maxima algorithm to minimize noise and detect significant movements.

The sensor's overall effectiveness was then evaluated through tests that measured changes in capacitance, consistency upon repeated pressure application, and linearity in response to increasing force.

Performance evaluation of the smart work shoes is conducted through experiments that include resolution evaluation using a load cell tensile compressor and a feasibility test with subjects ascending and descending stairs. The results show that the sensor can distinguish between stair ascending and descending with accuracies of 87.2% and 90.9%, respectively.

Figure 19 - PPE smart shoes design [27]

To conclude, the paper presents a novel approach to improving construction site safety using textile-based capacitive pressure sensors integrated in PPEs. The device's capabilities for real-time monitoring and accident warning show potential in significantly reducing the risk of fall-related accidents and injuries at construction sites with a cost-effective and non-restrictive application.

4.2 Sensor Shirt for monitoring of posture and movements in occupational health and ergonomics

In the published paper by Petz et al. [29] the authors present the development of a sensor shirt designed for real-time monitoring of the wearer's posture and movements, particularly for applications in occupational health and ergonomics.

Figure 20 - Sensor shirt with the position of the sensor nodes marked in orange [28]

The sensor shirt is equipped with several inertial sensors distributed across the upper body, which record movement and position data. These sensors are connected to a central processing unit that transmits the data via Wi-Fi. The sensor shirt system includes eight sensor nodes located in the neck, shoulder area, upper and lower arms, and lumbar vertebrae. An additional sensor node can be placed at the hip, which in the discussed prototype also serves as the data transmission hub. This node is equipped with Wi-Fi and Bluetooth capabilities and provides the power supply for the shirt. The individual nodes can be removed to allow for the washing of the shirt, and are connected to the shirt with snap fasteners, which are in turn connected with conductive stainless steel filament yarns.

Each sensor node is capable of measuring motion or environmental data and can preprocess this data. The nodes consist of a microcontroller and various sensors, including an accelerometer, gyroscope, magnetometer, humidity, and pressure sensors. The Sensor Tile board used for the motion detection tests contains a Cortex M4F microcontroller and the mentioned sensors, with a sampling rate of 100 Hz chosen for energy-efficient recording of posture and movement without significant loss of accuracy.

For energy and data transfer, conductive stainless-steel yarns are stitched to all nodes in a meander pattern. The data transmission utilizes additional conductive yarns, allowing for bus topologies such as single wire and serial link ring structures with UART for communication.

The initial measurements of the prototype demonstrate the shirt's potential and its applicability in occupational safety scenarios. The sensor shirt developed by the authors represents a significant advancement in smart textiles, offering a flexible and mobile platform for real-time monitoring of posture and movements, with potential applications in enhancing occupational health and safety.

4.4. Safety++ wearable systems for industrial safety

Guillermo Bernal et al. display in their paper [30] Safety++, an IoT ecosystem of connected wearable elements aimed at improving workplace safety in the energy industry. The authors argue that despite the availability of protective equipment and strict safety procedures, incidents still occur due to unsafe behavior, which is not adequately addressed by current solutions. Thus, it is emphasized the importance of real-time feedback, awareness, and peer communication in reinforcing safe practices and attitudes, that lead to a safer work environment in the field of energy production and transportation.

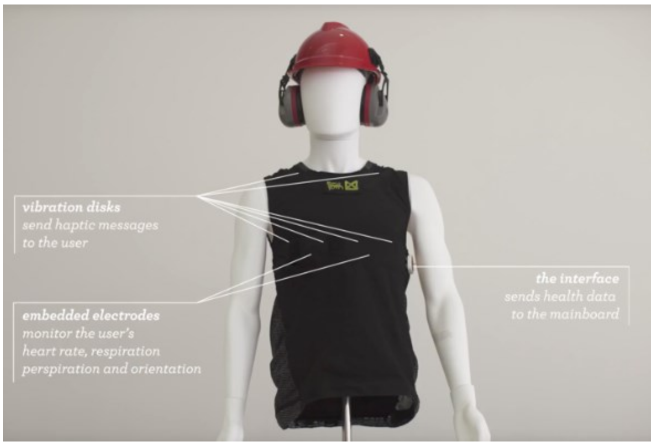

Figure 21 - Final vest prototype [29]

The first described element of this ecosystems consists of a smart vest that can gather information about the user's health conditions through a respiration sensor, a heart rate sensor, a galvanic skin response sensor, and a flexure sensor for posture monitoring. The vest is described as featuring a central processing unit in the upper back of the vest, acting also as a bridge that connects the vest to a second layer represented by the jacket, and its surrounding environment. The environmental data acquired by the jacket can be visualized and monitored by supervisor remotely on the dashboard, and in the case of an alarm an alert is sent to the worker wearing the vest by means of vibration.

Another element of the proposed ecosystem is a smart carabiner system equipped with a pressure sensor and wireless module that can promote safe worker habits by locking the toolbox if the worker is not safely tethered.

Finally, to prevent lumbar injuries and muscle strains through the promotion of movement awareness, shoes equipped with multi-layered linear force sensors are proposed by the paper, which can give feedback to the worker by means of a small vibration motor.

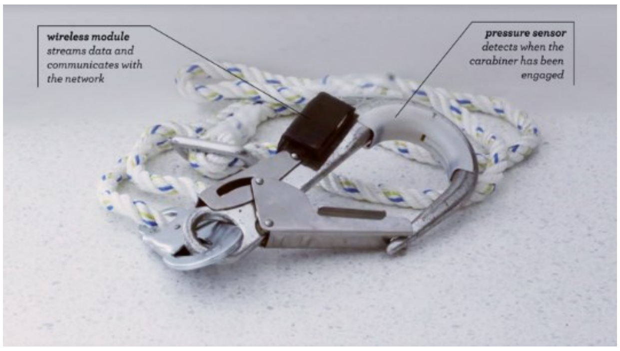

Figure 22 - the carabiner system [29]

Figure 23 - the Jacket final prototype [29]

The Safety++ project appears as an innovative approach to enhancing the safety of workers in the energy industry through a user-centered design of IoT and wearable systems. The devices and applications that are the focus of the paper include an ecosystem of wearable and connected devices that not only focus on connectivity but also on the communication of information between objects and workers and between people. This ecosystem is designed to continuously monitor vital signals like heart rate and to address four main safety issues: exposure to chemical and physical agents, man-down situations, falls from height, and load lifting.

Conclusion

The advent of wearable smart sensors in workplace applications marks a significant stride towards enhancing occupational safety and reducing work-related injuries. This thesis emphasizes the potential of such technologies in mitigating risks and promoting health within various industrial sectors.

However, the deployment of sensor-based safety management systems has numerous limitations and challenges that need to be overcome.

One of the primary challenges to the widespread adoption of these technologies is the stability and durability of the sensors, especially in harsh work environments. The cost-effectiveness of the implementation of these technologies also plays a key role in their success and needs to be further studied. Power supply requirements also pose a significant challenge, necessitating the development of self-powered or energy-harvesting devices to ensure continuous operation for the required work time.

Beyond technical barriers, ethical and privacy considerations need to be made when integrating sensor technologies into the workplace. The collection and monitoring of workers' physiological data and psychological derived data raise concerns regarding employee privacy and the potential misuse of personal information. It is crucial to establish clear guidelines and regulations that protect workers' rights and ensure that data collection is transparent, consensual, and used solely for the purpose of enhancing safety and health. Furthermore, the implementation of such technologies must also be approached with appropriate considerations for the comfort and acceptance of the workers wearing these devices.

In conclusion, while wearable smart sensors hold the promise of revolutionizing workplace safety, their successful integration depends on overcoming numerous challenges, both in terms of technical performance as well as in terms of users’ acceptability. Future research and development in this field must continue to focus on these areas to fully realize the benefits that these technologies can offer in enhancing occupational safety and health.

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