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A BRIEF REVIEW OF DEVELOPMENT OF SENSORS AND SHIELDING IN MEDICAL REHABILITATION SYSTEMS

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Abstract: *The development of wearable devices for medical recovery has led to an increase in interest in sensor systems capable of continuously monitoring the patient's functional parameters. This aspect has led to the creation of textile sensors integrated into wearable applications, which are capable of measuring the body's vital parameters, which are necessary for identifying various movement stages, such as gait or limb motion, as well as for the continuous and accurate monitoring of parameters such as pulse rate, or the continuous and precise verification of values such as those of the pulse. Also, the accuracy of the recorded data can be influenced by electromagnetic interference from the surrounding electronic environment, which can lead to signal noise and decrease in the fidelity of the measurements.*

Key words: *smart textiles, human motion analysis, composite sensor, screens, interference.*

1. INTRODUCTION

The increase in the number of strokes has led neuromotor recovery therapies to adopt much more precise systems for monitoring vital parameters, but also configurations that are included in wearable applications so that they do not add additional weight or create injuries to the user. In response to these challenges, these studies focused on sensor systems based on smart textiles or on systems from the soft robotics industry. The integration of sensors into wearable textile applications shifted the visual monitoring performed by the medical staff to a continuous, real-time one, where the systems can provide quantitative information on joint angles [1], strength [2], muscle activity [3] or compensatory movements developed by the patient during the execution of motor tasks [4].

The development of electromagnetic shielding (EMI shielding) for medical recovery systems has seen a significant technological advancement in the period 2024–2026. The focus has shifted from rigid (metal) solutions to flexible, lightweight and biocompatible materials, essential for wearable monitoring equipment, rehabilitation robots and magnetic/electrical stimulation devices.

Yang et al. [5] analysed shielding materials with multiple functions: self-healing, thermal management and fire resistance, which are essential for the safety of long-lasting physiotherapy equipment. Absorption shielding is highlighted, instead of the reflection of waves, an element that helps reduce the effects of electromagnetic radiation. Xu et al. [6] highlighted the use of conductive polymers and the key factors that are used in the selection of conductive polymers, the design of chemical devices and the architecture of devices are highlighted. As materials used, hydrogels, elastomers and conductive composites are mentioned.

Another direction of research is given by the development of smart textiles that protect cardiac or muscle monitoring sensors against interference in the hospital environment. For this, smart biocomposites are used to monitor the structural condition. The challenges and prospects for the conversion of smart biocomposites are highlighted [7]. The aim is to directly integrate biocomposites into compression garments used in physical therapy but also to reduce negative influences (radiation, noise, etc.) in the treatment rooms.

Therefore, the development of devices for medical recovery requires a complex, component-based approach, in which sensor systems provide information on movement, force or bioelectrical activity, and electromagnetic shielding materials ensure the functional compatibility of these systems in real-world environments. The correlation of the two directions thus becomes essential for the realization of wearable systems capable of combining comfort, measurement accuracy and signal quality. This paper aims to study medical recovery systems that have integrated elements from the smart textile industry both for the monitoring process of vital parameters and for the protection of electromagnetic interference between devices and integrated electronic circuits.

2. SENSOR SYSTEMS USED IN MEDICAL RECOVER

Zhou et al. [8] developed a composite sensor based on graphene, TPU (thermoplastic polyurethane) and textiles with good properties in terms of electrical conductivity, UV resistance and durability over time. As a development principle, this sensor was based on the integration of a graphene-based conductive material into an elastic textile substrate sealed with a flexible polymer.

The textile substrate was obtained by knitting fibers with 90% acrylic and 10% Spandex in the structural composition. The conductive layer was obtained from graphene oxide [8]. From a functional point of view, the sensor has the ability to transform the deformation produced by the flexion-extension movement of the foot joint into variations of electrical resistance measured to correlate these values with the value of the angle of the joint. After calibration, this system was able to be included in a muscle training system where patients could control a character in a video game. The configuration proposed by the authors demonstrates the ability of this wearable system to accurately measure the angle of the knee by processing electrical signals in angular positions with the help of prior calibrations, so that it can be included in the medical recovery process with wearable devices.

In another paper [9], the authors aimed to create a system that can be positioned on the body capable of providing measurements on the movement of the joints, with emphasis on two relevant quantities in the functional analysis of the hand, namely the angle of flexion and the force exerted during movement. These two characteristics are important for characterizing the stages of motion, as they reflect both the amplitude of motion and the capacity to generate force. In this regard, the proposed solution consisted of a hybrid, self-powered sensor system that combines triboelectric and piezoelectric principles to overcome the limitations of conventional sensors, such as low sensitivity, the influence of environmental factors or the need for external power.

The triboelectric sensor is sensitive to deformation and allows the bending angle to be monitored, but its performance can be affected by environmental conditions and wear. In contrast, the piezoelectric sensor exhibits an adequate response to force variations, but is limited in sensitivity and signal-to-noise ratio. By combining these into a composite architecture, the system becomes able to distinguish between geometric deformation and mechanical stress, making it suitable for monitoring applications in neuromotor rehabilitation. The triboelectric sensor was used to determine the flexion angle and was made of Ecoflex. Its structure has two electrodes positioned on the same surface of the elastic layer. The resulting electrical signal is directly correlated with the bending angle, increasing with it.

The piezoelectric sensor was intended for force monitoring and was made of a layer of PVDF-HFP (polyvinylidene fluoride-co-hexafluoropropylene) electrospun nanofibers doped with BaTiO3 and PEI (polyethyleneimine) nanoparticles, having PEDOT:PSS (poly(3,4-ethylenedioxythiophene) polystyrene sulfonate) electrodes deposited on both sides. It provides an electrical response correlated with the applied force, allowing the separation of information related to mechanical stress from that associated with geometric deformation. The testing carried out was possible with the help of 20 volunteers, indicating small variations in the signal, with a margin of error of approximately 0.1–0.5 %, which supports the feasibility of using the system in the monitoring of neuromotor rehabilitation.

Lo Presti et al. [10] proposed a study on the development of a sensor system intended to identify the movement of the muscles at the trunk level. The authors developed a system of seven flexible sensors, based on the signal transmission behavior of an optical fiber, to monitor the additional movements performed by the patient as a result of spasms.

From a structural point of view, the system consists of an assembly of seven flexible sensors based on FBG (FBG – Fiber Bragg Grating), integrated into a wearable structure positioned along the spine, from the cervical to the lumbar area. These sensors were connected to an optical interrogation unit, responsible for detecting variations in reflected wavelength, as well as to a data acquisition and processing system. The choice of FBG sensors is justified by their high sensitivity to deformations, mechanical flexibility and the ability to measure variations distributed along a surface, which allows the faithful capture of trunk movements without restricting the user's mobility [10].

The operating principle is based on the modification of the wavelength reflected by the optical fiber following its deformation, a phenomenon that occurs as a result of the stretching or compression generated by the movement of the trunk. Thus, the movements of the body cause variations in the optical signal, which are subsequently correlated with the amplitude and direction of movements. This approach allows the transformation of biomechanical movements into signals, providing an indirect but accurate method of evaluating motor behaviour [10].

The evaluation of trunk movements was carried out using kinematic landmark sensors and a MoCap motion capture system, which served as a reference for the validation of the system based on FBG sensors. The kinematic pointers were represented by reflective points attached to different areas of the trunk, in correspondence with the positions of the wearable sensors, which are used to track the spatial movements of the body. The MoCap system works on the basis of optical cameras that detect the position of these markers in space and reconstruct their three-dimensional trajectories in real time, thus providing a direct and accurate measurement of movements [10].

The sensor system was designed to monitor the human trunk movements. Thus, the movements performed by the patients to move certain objects were followed. The additional movement that people who have suffered a stroke usually make, moving the shoulder towards the object, is followed. The additional shoulder movement causes deformation of the sensors mounted on the patient, and together with the movements monitored by the kinematic markers, these movements are identified. This aspect emphasizes the loss of neuromotor capacities with the passage through this medical event. Thus, by comparing the results achieved on healthy and post-stroke patients, trends in the use of elbow muscles are observed even when there were constraints on not using them. Therefore, the integration of this monitoring system was able to correctly identify the muscle activation patterns, both for healthy patients and those with neuromotor difficulties, its accuracy making it feasible for inclusion in monitoring systems in medical recovery [10].

3. SHIELDING AND SENSORS PROTECTION

In the field of smart fibers, it is very often used in applications such as: pressure sensors, temperature sensors, motion sensors, acoustic sensors, optical sensors. Thus, a developing field that has attracted the attention of researchers is textual, the combination of textiles and elements belonging to electronics.

A review of textronics for monitoring the body's vital signals from the perspective of integrating sensors at various levels of the textile manufacturing process chain—fiber, yarn, fabric, and clothing—is presented. Although a large number of research methods and prototypes have been developed, there are few details on the holistic quality and suitability of each approach for personalized and ubiquitous health monitoring systems. Several research reviews on wearable textile platforms provide recommendations for mechanical and chemical performance of the textile. The authors also recommend the analysis and clear reporting of biocompatibility, safety, comfort, experimental conditioning and pretreatment for the textile sensor system. On the other hand, studies on body-worn sensor networks (BSNs) identify and define critical performance parameters for successful BSNs, such as interoperability, reliability, security, validation, and sensor signal accuracy. It is also concluded that a textronic system must fulfil its double purpose, both as a biomedical sensor and as a clothing item, and the two aspects are inexorably linked. Characterization testing for textronics is thus affected by interdependencies. Only a coordinated interaction of textronic in a textile platform and a biomedical sensor should lead to the realization of a successful textronic system [11].

Textronics is the combination of textiles and electronic technologies, enabling the creation of smart textiles and e-textiles capable of measuring, reacting or communicating. The field includes sensors integrated into clothing, conductive materials, nanotechnologies and IoT solutions. The main applications are in medical, sports, safety, fashion, automotive and soft robotics. The major challenges are energy supply, durability in washing and stable integration of electronic components. Future trends include renewable energy textiles, integrated AI and sustainable materials [12].

Biosignals often need to be detected in sports or for medical reasons. Typical biosignals are pulse and ECG (electrocardiogram), breathing, blood pressure, skin temperature, oxygen saturation, bioimpedance. Long-term measurements on mobile patients or athletes require other equipment. Here, textile-based sensors and data connections embedded in textiles are preferred to avoid skin irritation and other unnecessary limitations of the monitored person. Thus, it is necessary to include communications, a power supply and a data processor.

Although the full integration of sensors and additional electronics into textile fabrics is not always easy at the recent stage of technology. Electrodes in direct contact with the skin can be prepared from a more skin-friendly material and in more comfortable shapes than, for example, ordinary ECG electrodes or the relatively rigid chest straps known from heart rate measurements in sports. Thus, a long-term ECG electrode based on textile electrodes and electronics integrated into textiles should be much more comfortable than the still common version.

So, the diverse and partially chemical physical properties of humans can be measured by textile sensors. For measuring electrical properties such as resistance, impedance, voltage or capacitance, which are possible through fibers, wires or conductive layers, and sometimes also through fine metal wires. The main challenges in the development of textile biosensors are the following: high contact impedance between dry skin and textile electrode; whether the sensors detect signals directly on the skin; and unwanted changes in the resistance and other electrical properties of the sensors, due to washing and wear [13].

Thus, passive wireless sensors are becoming increasingly important in industry, health and environmental monitoring. Among the advantages, it can be mentioned that it does not require batteries. They can operate in extreme environments (temperature, pressure). About the dimensions they are small, cheap and easy to integrate. For these sensors, the need for new materials with low dielectric losses and high stability is highlighted. A future area for improvement concerns the optimization of reading distance and noise immunity. Due to the promising results, the integration of nanogenerators for fully autonomous sensors can be tried [14].

In study [15] Zhang et al. presented the development of a flexible sensor based on Ni/CCF@PDMS (CCF–chopped carbon fibers, PDMS–polydimethylsiloxane), intended for monitoring bioelectrical signals such as sEMG (surface electromyography) and EOG (electrooculography) in environments with electromagnetic interference. The objective of the paper is to obtain a flexible structure capable of ensuring good contact with the skin and protection against electromagnetic interference, for the stable recording of weak biosignals.

The sensor was obtained by dispersing nickel particles and carbon fibers in the PDMS matrix, followed by mixing, ultrasonication, degassing, and mold casting, and then by printing Ag/AgCl electrodes on the flexible substrate. From an experimental point of view, the authors compared the Ni/CCF@PDMS sample with several reference variants and carried out tensile, adhesion, and electromagnetic shielding tests. The proposed variant provided a balance between deformation and breaking stress, reaching a deformation of 55.6% at a stress of approximately 1.49 MPa, and demonstrated an electromagnetic shielding effectiveness of 39.82 dB.

The feasibility of using the sensor was verified through sEMG measurements at the forearm level and EOG measurements during natural and forced blinking. The results highlighted stable signals, with reduced background noise, and a clear differentiation between the types of muscular contractions and blinking, confirming the potential of the sensor for biomedical monitoring applications.

4. CONCLUSIONS

This paper briefly reviews the accelerated evolution of flexible sensors, materials for medical recovery and emphasizes the need to integrate two major directions: advanced sensor systems for monitoring physiological signals and shielding materials. The reviewed studies demonstrated that the integration of flexible sensor systems with electromagnetic shielding materials represents a viable solution for the continuous and accurate monitoring of biomechanical and bioelectrical parameters in post-stroke patients.

Thus, the correlation between the 2 directions (flexible, hybrid or optical sensors and materials) is important in achieving an electronic system capable of being comfortable, accurate and reliable. Development in this direction is useful for creating a system with high potential in the medical field. Integration of advancements in interrelated areas is a future task.

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