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Wearable Biosensor Technologies

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ABSTRACT: This paper aims to review the various technologies behind wearable biosensors and where there are areas for improvements to be made. The theoretical foundation of this paper was formed by conducting a comprehensive literature review on wearable biosensors. There are three main biosensor technologies that are presented in this paper. The three main wearable biosensor technologies that are most prominent include accelerometers and motion sensors, biochemical sensors, and photoplethysmographic sensors. The empirical research that was used is limited to 15 papers from relevant conferences and journals associated with the medical device industry. Wearable biosensor technologies clearly have several clinical applications that make them one of the most appealing tools in the medical device industry. This paper illustrates that wearable biosensor technologies definitely have the capability to make a significant impact on the medical device industry because of their compact and diverse nature.

KEYWORDS: Wearable Biosensors, Wearable Biochemical sensors, Photoplethysmographic Sensors, Accelerometers, Biosensor Technologies.

1 INTRODUCTION

Wearable biosensors have many types of clinical applications. Some of their current capabilities include physiological, biochemical, and motion sensing for both diagnostic and monitoring applications [1]. They can also play a major role in the treatment of chronic diseases by contributing information for precise titration of therapy or detecting patient compliance lapses [2]. Wearable biosensors have the potential to revolutionize healthcare through low-cost and pervasive physiological monitoring. The continuous and noninvasive measurements of cardiovascular functions help to promote healthy lifestyles, monitor for cardiovascular catastrophes, and determine the impact of clinical interventions [3]. It is their ability to comfortably and continuously monitor cardiovascular activity for long periods of time outside the clinical setting that is most appealing.

The influence of motion artifacts must be taken into consideration during the design and placement of wearable biosensors for them to be practical and effective in the field. They should be unobtrusive and comfortable to wear, lightweight, robust, and provide reliable sensor attachment [3]. In addition, other design considerations should include compactness, stability of signal, motion and other disturbance rejection, durability, data storage and transmission, and low power consumption [2]. These devices must be able to be worn by people just like regular clothing, but still be capable of performing their desired functions [4]. It is important for wearable biosensors to address these design needs in order for them to have the versatility for multiple clinical applications.

There are several types of technologies utilized by wearable biosensors. This paper will detail three prominent mechanisms applied by these devices, which are accelerometers and motion sensing, biochemical sensors, and photoplethysmographic sensors. Accelerometers have a practical application for determining physical activity because of the linear relation between motion close to the body's center of mass and energy expenditure [5]. This relationship enables these types of devices to be suitable for physical therapy and rehabilitation applications. Accelerometers can be used in conjunction with other biosensors to measure exercise routines and fitness regimens as well. They are especially valuable when combined with wireless heart rate and electrocardiogram (ECG) monitoring [5], [6], [7].

Biochemical sensors have a variety of clinical applications due to their extreme flexibility and versatility. They are capable of real-time on-body monitoring of chemical constituents, which can yield significant additional insights into the overall health status and performance of individuals when compared to that obtained by monitoring physical variables alone [8]. These types of sensors can be utilized for non-invasive sweat monitoring through epidermal tattoo potentiometric sodium sensors with wireless signal transduction [8]. Also, they are used for one-point wireless ECG acquisition with flexible poly-dimethylsiloxane (PDMS) electrodes [9]. Similarly, we can apply the same principles for an optical fiber biosensor consisting of polyacrylamide (PAAM) hydrogel to measure EEG signals and lead to contactless electrodes [4].

Photoplethysmographic sensing technology is commonly used for wearable biosensors because of its noninvasive nature and reliable accuracy. These types of sensors can be compact and efficient, which is clearly evident by the wearable photoplethysmographic ring sensor for mobile monitoring [2]. This mechanism has been reduced to an even smaller scale with the development of magnetic earring biosensors integrated with wireless earpieces used to measure heart rate and ECG [3]. Also, the technology has been expanded to be used in conjunction with smart phones for continuous mobile vital sign monitoring through wearable photoplethysmographic biosensors [10]. Photoplethysmography has several prominent clinical applications and it has been further developed with biosensors to increase mobility and convenience.

It is clearly evident that accelerometers and motion sensing, photoplethysmographic sensors, and biochemical sensors are three of the main technologies behind wearable biosensors. There has been a significant amount of research already conducted in this area of interest, and this paper will present and analyze some of the current applications of these types of sensors. The feedback that is presented will illustrate that there is always room for refinement in any design especially those dealing with the medical device industry. It is quite obvious that the world of biosensors is a constantly evolving field, and the more noninvasive they can be made will be beneficial to their clinical significance. The principle of patient safety must always be the taken into consideration when reviewing any medical device design.

2 RESEARCH METHOD

The research in this paper concentrates on the different technologies used by wearable biosensors. There are three main technologies that are presented, which include accelerometers and motion sensors, biochemical sensors, and photoplethysmographic sensors. The theoretical foundation behind this paper was built around the review of current journal and conference papers dealing with wearable biosensors. This type of review-centric approach is necessary in order to gain a better understanding of the field of interest and the current state of its technology. Once we become familiar with the work and opinions of the experts in the area of study, then we can form our own ideas and conclusions based on our interpretation of the information. Also, we must be aware of the latest technology in the field in order to have a firm grasp on what is considered state of the art. We can produce the most significant contribution and offer any new insight into the area of study from this style of approach.

3 RESULTS AND DISCUSSION

Table 1. Wearable Biosensor Technologies

Accelerometers and Motion Sensors	Reference
Accelerometer with ECG necklace	[5]
Accelerometer and wireless heart rate monitor	[6]
Motion sensor algorithm	[7]

Biochemical Sensors	Reference
Epidermal tattoo potentiometric sodium sensor	[8]
Flexible PDMS electrode	[9]
Flexible thick-film glucose biosensor	[11]
Hydrogel-based (PAAM) photonic sensor	[4]
Textile based patch with optical detection system	[12]
Knitted fabric biocloth	[13]
Ion-selective electrodes	[14]

Photoplethysmographic Sensors	Reference
Photoplethysmographic ring sensor	[2]
Photoplethysmographic biosensors with smart phones	[10]
Photoplethysmographic ECG magnetic earring and wireless earpiece	[3]
Photoplethysmographic biosensors with Galvanic skin response	[15]

3.1 ACCELEROMETERS AND MOTION SENSORS

The various wearable biosensor technologies and applications that will be reviewed in this paper are shown in Table 1. There has been significant research conducted involving the use of accelerometers and motion sensing with biosensors. Wearable accelerometers and heart rate sensors have been widely used to monitor physical activity and estimate energy expenditure [5]. The growing interest in physical activity and energy expenditure is due to their role in the relationship between human behavior and health status. It has been proven that cardiorespiratory fitness is the main reason behind individual heart rate fluctuation during physical activity. An individual with high cardiorespiratory fitness will have a lower heart rate during physical activity, compared to that of an individual with low cardiorespiratory fitness [5]. The research shows that through the implementation of a wireless ECG necklace along with a three-axial accelerometer and an indirect calorimeter, we can successfully measure energy expenditure from a normalized heart rate measurement that factors in cardiorespiratory fitness of the individual [5]. The heart rate can be normalized to factor in cardiorespiratory fitness by taking measurements from different individuals during a constant workload.

A similar approach was taken with heart rate monitoring involving dynamic movements. We know that it is important to monitor heart rate variability with physical activity because it is a vital indicator of cardiac status [6]. The research conveys that a wearable system can be developed to simultaneously monitor heart rate and body accelerations, which consists of a wireless triaxial accelerometer, wireless heart rate monitor, 12bit A/D converter, and microcontroller with Bluetooth stack [6]. This system was used to collect data from various subjects that would remain still at first for heart rate stabilization, and then perform activities like lying, standing, sitting, walking, running, and falling. The triaxial accelerometer was worn on the waist by each individual in a belt and the heart rate monitor was attached to their chest. The output voltage of each axis generated by the accelerometer was calculated and the acceleration data as well as the mean heart rate values were transmitted to a personal computer for data analyses [6]. Also, the heart rate is derived from a precordial ECG lead and is commonly estimated by the inverse of the time interval between the peaks of adjacent R waves in the ECG [6].

There is much research regarding the effectiveness of physical therapy sessions and how they can be improved. The evaluation of the individual exercises during the therapy sessions is crucial to accurately assess this effectiveness. The research proposes a multi-template multi-match dynamic time warping (MTMM-DTW) algorithm as a natural extension of DTW to detect multiple occurrences of more than one exercise type by using wearable motion sensors [7]. The motion sensors are small and lightweight so that they do not affect any movements, which enable a specialist to record reference templates for each exercise. The system then compares these detected movements with the templates recorded while under supervision, and quantifies their similarity as part of the evaluation process [7]. The wearable motion sensors consist of three tri-axial devices: an accelerometer, a gyroscope, and a magnetometer that are all positioned to capture leg and arm movements only. These sensors can be freely configured for each exercise and template, but the same configuration should be used during the recording of the templates that is used while exercising [7].

3.2 BIOCHEMICAL SENSORS

The integration of biochemical sensors into the wearable biosensor technology has become much more prominent within the last ten years. The research describes the application of an epidermal temporary-transfer tattoo-based potentiometric sensor coupled with a miniaturized wearable wireless transceiver for non-invasive sweat monitoring [8]. It has been proven that the monitoring of sodium in human sweat reflects electrolyte imbalance, which is a good indicator of our general health status and well-being. There is an obvious need for a wearable device that quantifies the real-time transient sweat sodium concentrations and could alert the individual about their electrolyte loss and the subsequent need for electrolyte replenishment [8]. The epidermal tattoo sodium ion-selective electrode sensor was fabricated through the amalgamation of thick film, laser printing, solid state potentiometry, fluidics, and tattoo-transfer technologies [8]. The research shows that this type of sensor displays a rapid near-Nernstian response with negligible carryover effects, and good resiliency against various mechanical deformations experienced by the human epidermis [8].

A related approach was taken for the application of flexible poly-dimethylsiloxane (PDMS) electrodes in wireless ECG monitoring. The research presents a novel flexible PDMS dry electrode (FPDE) that is constructed with gold as a contact layer is bio-compatible with skin and PDMS [9]. It has been proven that the gold adhesion strength on PDMS surfaces can be deteriorated by metal deposition, so this type of electrode surface was treated with a carbon dioxide laser to increase the surface roughness from nm to µm scale, allow for gold to be stably adhered by physical deposition and patterning, and increase the adhesion ratio up to 57% [9]. The FDPE was used in conjunction with a wireless ECG acquisition circuit that consisted of four parts: front-end amplifiers, filters, wireless transceivers, and a power supply. In addition, the FDPE has an integrated instrumentation amplifier, wireless transmission module with an integrated 12-bit analog-to-digital converter, voltage regulator to amplify and filter the ECG signals, and a preamplifier band-pass filter was embedded into the circuit board for ECG acquisition [9]. The combination of all of these components enables the device to easily communicate with a computer, which provides a suitable solution for mobile ECG acquisition applications.

A similar approach was taken for the development of flexible screen-printed electrodes (SPE). This type of technology can be utilized for glucose biosensors, which have an obvious application in the management of diabetes. The screen-printing technology involves printing patterns of conductor and insulators onto the surface of planar substrates in which different conducting and insulating ink materials can be used for this task in connection to rigid (ceramic) or flexible (plastic) substrates [11]. The development of wearable and flexible screen-printed biosensors requires proper attention to be paid to the influence of mechanical stress that may be induced from bending during daily activities on both the electrochemical behavior and sensor performance [11]. The research examines this mechanical influence on the amperometric biosensing of flexible glucose oxidase (GOx)/Nafion-coated SPE [11]. It has been proven that these types of sensors operate well following a severe bending-induced mechanical stress, and actually display a substantial sensitivity enhancement following their mechanical bending [11]. However, this sensitivity enhancement is observed only for the amperometric detection of glucose substrate and not for measurements of hydrogen peroxide, catechol, or ferrocyanide at coated or bare SPE [11]. The research conveys that the bending effect is associated primarily with changes in the biocatalytic activity, and the sensitivity enhancement is more pronounced at elevated glucose levels [11].

A similar application involves the implementation of polyacrylamide (PAAM) hydrogel for an optical fiber biosensor used in the acquisition of electroencephalogram (EEG) signals. The mechanism behind this technology involves the use of a bioelectric signal to drive an electro-optic material or device that will manipulate light and change its properties, which gives origin to an optical signal that is converted into the original EEG signal [4]. The research presents a new type of photonic sensor for a wearable brain cap to record the scalp electrical signals and enable the possibility of a contactless record of EEG [4]. This type sensor of must measure biopotential and be comfortable to wear, so the reference electrode was placed on the back of the neck for optimum results. The main functional stages of the sensor are optical signal generation, control and modulation, and detection in which the modulated light is guided to a photodetector for measurement [4]. This light property modification observed is proportional to the actual biopotential that enables the translation of this result into a biopotential recording [4]. The PAAM hydrogel was used as the sensing component because an input light that is passed through this hydrogel will experience modifications, not only regarding the refractive index, but also the amount of light that is transmitted back to the photodetector [4].

An analogous approach was taken for the development of a textile based patch biosensor with an integrated optical detection system for sweat monitoring. It has been proven that sweat contains very rich information about the physiological condition of an individual because it contains a matrix of essential ions and molecules [12]. Also, sweat analysis is known to be used to identify pathological disorders like cystic fibrosis and real-time sweat analysis during exercise can give valuable information on dehydration as well as changes in the amounts of these biomolecules and ions [12]. The research conveys that a sweat collecting fluid handling platform using fabrics with inherent moisture wicking properties can provide this real-time analysis by incorporating a passive pump to gather sweat and move it through a pre-defined channel for analysis [12]. A colorimetric approach was used for sweat pH measurement involving a pH sensitive dye that changes color depending on the pH of the sweat, and this color change was detected by diffuse reflectance measurement using an emitter-detector LED technique [12]. The quantitative pH measurements were obtained by a paired emitter-detector dual LED configuration in which the detector LED is reverse biased at a specific voltage, and the photocurrent generated upon incident light then discharges the LED at a rate that is proportional to the intensity of light reaching the detector [12].

A related approach involves the application of knitted fabric bioclothes for cardiopulmonary monitoring. We know that there is an obvious need for the continuous remote monitoring of patient vital signs in order to improve initial clinical treatment and their rehabilitation process. The research proposes a system with conductive and piezoresistive materials in the form of fiber and yarn that are used to realize clothes where knitted fabric sensors and electrodes are distributed and connected to an electronic portable unit capable of detecting, acquiring and transmitting physiological signals [13]. This knitted fabric platform contains insulated conductive tracks connected with sensors and electrodes in which there are cloth strain fabric sensors based on piezoresistive yarns and fabric electrodes realized with metal based yarns to enable the realization of wearable and wireless instrumented garments capable of recording physiological signals [13]. The sensitive garment can be wirelessly integrated with the WEALTHY monitoring system in order to process and analyze the patient physiological data remotely [13].

Another approach taken has to do with the application of ion-selective electrodes (ISE) in environmental monitoring and wearable sensors. It has been proven that ISEs are electrochemical sensors that offer an easy-to-use and cheap tool for the analysis of several ions found in natural waters and bodily fluids [14]. These types of sensors can be utilized in the analysis of electrolytes in real blood samples as well as sweat, saliva, and other interstitial fluids needed for point-of-care and self-diagnostics [14]. The research details solid-contact ISEs (SC-ISEs) in which the internal reference electrode and the inner filling solution are replaced by a solid material which should be nonpolarizable upon the input current of the measuring amplifier and have suitable redox and ion-exchange properties [14]. Ultra-microelectrodes (UMEs) were also discussed in the research as a method to miniaturize ISEs, but they may cause lower potential stability because of smaller redox or double-layer capacitances, leakage of membrane components, adherence and exfoliation of membranes [14].

3.3 PHOTOPLETHYMOSGRAPHIC SENSORS

There has been significant research regarding photoplethysmographic sensors as part of the wearable biosensor technology. One approach involves the application of a photoplethysmographic ring sensor for mobile monitoring. It has been proven that this ring sensor is capable of reliably monitoring a patient's heart rate, oxygen saturation, and heart rate variability [2]. We know that the finger is one of the best places for sensor attachment because its primary vasculature is located near the surface and therefore makes it optimal for monitoring arterial blood flow using noninvasive optoelectronic sensors [2]. However, this type of sensor must be able to eliminate front-end signal artifact that can be attributed to fluctuation in the amount of photon absorption from nonpulsatile physiological components as well as the exposure to diverse ambient lighting conditions to improve overall signal quality [2]. The research presents a prototype that contains an optical sensor unit, analog and digital processing units, RF transmitter, all of which are encapsulated in a compact body and powered by a tiny cell battery used for wristwatches [2]. In addition, the ring has a PIC microcomputer that performs all the device controls and low-level signal processing, including LED modulation, data acquisition, filtering, and bi-directional RF communication [2]. The research also details subsequent prototypes with design improvements intended to address specific difficulties such as motion artifact resistance and accuracy, lower power consumption, local pressurization, and motion detection [2].

A similar approach was taken for the integration of a smart phone platform with photoplethysmographic biosensors for continuous health monitoring. It is clearly evident that the popularity of smartphones with their open operating systems provides a powerful platform for developing very low-cost personalized healthcare applications [10]. The research details this platform that is made up of three key elements: the wearable biosensor, the controller for the biosensor, and the mobile monitoring unit [10]. The wearable photoplethysmographic biosensor has Bluetooth communication capability and monitors the following physiological signals: pulse rate, breathing rate, oxygen saturation (SpO2), and obstructive sleep apnea (OSA) prediction [10]. These signals are determined through the implementation of signal processing algorithms such as Fast Fourier Transform (FFT) and Discrete Fourier Transform (DFT) in the Java based mobile phone software interface [10]. Also, the system has three different operating modes consisting of OSA monitoring, general mode, and simple mode. The OSA mode estimates the likelihood of OSA and reports the results to the user, while general mode and simple mode measure the pulse rate, breathing rate, and SpO2 so that they can be either displayed graphically or numerically [10].

A related approach was taken for the development of a magnetic earring sensor and wireless earpiece designed for photoplehtysmographic ECG monitoring. It has been proven that the earlobe is an attractive measurement site because it has a rich arterial supply and is less affected by motion than other extremities [3]. The research presents an earring sensor consisting of a nickel-plated neodymium magnet insulated with electrical tape on both sides, and serves as the substrate for mounting a reflective photosensor on one side as well as a three-axis accelerometer on the other to perform adaptive noise cancellation (ANC) [3]. Also, the reflective photosensor is made up of a phototransistor and an infrared (IR) LED in a single package with a layer of epoxy applied around it to protect the wire connections and stabilize the sensor [3]. The earring sensor can be worn against one side of the earlobe by attaching another neodymium magnet to the opposite side since they are strong enough to hold the sensor in place even in the presence of motion [3]. The reflective photosensor shines an IR light into the earlobe and measures the amount of light reflected from the subcutaneous blood vessels in which changes in the amount of reflected light indicate the timing of cardiovascular events during the cardiac cycle [3]. The entire system was designed to fit into a standard Bluetooth wireless earpiece because of its increasing popularity and overall acceptance of these communication devices [3].

Another approach involves the development of wearable photoplethysmographic biosensors as part of stress level analysis for automotive drivers. It has been proven that task induced modifications in rhythms of physiological signals acquired during real-time driving are clinically proven hallmarks for quantitative analysis of stress and mental fatigue [15]. It is important in a real-time driving scenario to detect the incremental changes in emotions as well as the fatigue and stress level of the driver [15]. The research proposes a multimodal sensor-compute infrastructure consisting of a body-worn clip-on pulse oximeter, abdominal respiration belt, and Galvanic Skin Response (GSR) Velcro electrodes [15]. We know that GSR signal is induced and triggered as a result of occurrence of stressful events, but is not as versatile as photoplethysmography because of its ability to extract multiple parameters like heart rate, SpO2, and respiration rate [15]. The acquisition of these various physiological signals requires extensive signal processing techniques in order to extract any clinically significant data. These signals are then used in conjunction with an artificial neural network (ANN) to classify various driver stress states during different scenarios.

4 CONCLUSIONS

It is clearly evident that accelerometers and motion sensors, biochemical sensors, and photoplehtysmographic sensors are the most prominent wearable biosensor technologies. We know that each of these technologies has specific challenges that need to be addressed during the sensor design process. Accelerometers and motion sensors require the integration of another wearable physiological monitoring device as well as some type of computer software interface equipped with specific algorithms for signal manipulation and analysis. Biochemical sensors have more complex requirements concerned with the biocompatibility and other chemical properties of the human body. There must not only be consistent sample delivery to the active surface of the sensor, but also the long term stability of the sensing interface. In addition, low sample detection limits that require cumbersome and repetitive sensor calibration are other common issues. There are multiple environmental factors that must be considered including the sample having active interferences to overcome and biofouling in the joint of the sensor. Photoplethysmographic sensors have the motion artifact challenge that needs to be addressed in order to ensure optimum signal quality. These types of sensors must deal with the fluctuation in light absorption from the exposure to various ambient lighting conditions as well. We know that all of these sensors must be comfortable and compact enough so that they can be worn everyday just like regular clothing. It is from this perspective that we must always take the overall safety of the patient into account during the sensor design process. The overall accuracy of accelerometers and their integration with physiological monitoring definitely could be addressed in the future to improve precision and effectiveness. The extreme versatility and flexibility of biochemical sensor applications make them always a candidate for further investigation and analysis. There may be more efficient methods to attenuate the effects of diverse ambient lighting conditions on photoplethysmographic sensors. It is quite obvious there is a need for additional research into developing more technologies involving wearable biosensors because of their significant appeal for mobile monitoring in the medical device industry. This will provide us with even more methods to effectively monitor patients and provide healthcare practitioners with additional tools at their disposal.

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