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CHARACTERISTICS OF TATTOO ELECTRODES AND FLEXIBLE ELECTRONICS AND THEIR APPLICATIONS IN THE ADQUISITION OF BIOMEDICAL SIGNALS

CARACTERÍSTICAS DE LOS ELECTRODOS DE TATUAJE Y ELECTRÓNICA FLEXIBLE Y SUS APLICACIONES EN LA ADQUISICIÓN DE SEÑALES BIOMÉDICAS

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KEYWORDS: electrodes, tattoo electrodes, flexible electronic, electrophysiological signals, biocompatibility.

Abstract

Focused on solving the problem of adherence to the skin and the quality of the bioelectrical recordings, new devices that have emerged such as tattoo electrodes and flexible electronics, which prove to be a novel and viable technology, capable of improving the quality in electrophysiological signal studies and patient comfort. The use of electrodes or medical patches to capture bioelectrical signals is of utmost importance for the diagnostic of different pathologies, as is the need for devices that are biocompatible with human skin and are effective when capturing these signals. This article presents a study of the state of the art on the main characteristics and applications of tattoo electrodes and flexible electronics in biomedical signal measurement processes and the benefits, it offers compared to used medical electrodes.

PALABRAS CLAVE: electrodos, electrodos de tatuajes, electrónica flexible, señales electrofisiológicas, biocompatibilidad.

Resumen

Centrados en resolver el problema de la adherencia a la piel y la calidad del registro de las señales bioeléctricas, han surgido nuevos dispositivos como los electrodos para tatuajes y la electrónica flexible, que resultan ser una tecnología novedosa y viable, capaz de mejorar la calidad en los estudios de señales electrofisiológicas y la comodidad del paciente. El uso de electrodos o parches médicos para la captación de señales bioeléctricas es de suma importancia para el diagnóstico de diferentes patologías, así como la necesidad de contar con dispositivos que sean biocompatibles con la piel humana y que sean eficaces en la captación de estas señales. Este artículo presenta un estudio del estado del arte sobre las principales características y aplicaciones de los electrodos de tatuaje y la electrónica flexible en los procesos de medición de señales biomédicas y las ventajas que ofrece en comparación con los electrodos médicos utilizados.

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INTRODUCTION

Different processes occur within the human body that can be captured as signals with relevant information about the health of the human being (Silva & Tavakoli, 2020). These signals are recordings of biological events that occur inside the body, where epidermal electrophysiology is very useful to monitor the activity produced by muscles, heart and brain (Wang et al., 2020). Our body is made up of different cells that, presenting electrochemical changes within them, produce signals that can be transmitted through the biological medium (e.g., skin), and in this way can be captured.

The detection of bioelectrical signals using sensors is a widely used approach for the diagnosis of diseases (Wang et al., 2020). Surface electrodes (SEs) have a role as a means to collect electrophysiological signals in a non-invasive manner (Wu et al., 2021). However, available sensors may have limitations in the recording of electrophysiological signals (Schnyer et al., 2017).

The use of needle electrodes is considered one of the most effective methods for recording bioelectrical signals, in which the electrode is inserted through the skin (Fernández, 2017). However, the main drawbacks of using needle electrodes is its invasive nature, in addition to being an uncomfortable process for the patient, and therefore it must be performed by a trained professional (Fernández, 2017).

SEs allow for noninvasive recordings, which has popularized their use in many clinical fields in recent years. However, SEs have certain limitations, as a wet medium (conductive gel) is needed to improve coupling with the skin. In addition, on many occasions, the adhesion capacity of surface electrodes to the skin is not the ideal, which means that, in many cases, reinforcements must be used, for example, using adhesive tape, which is cumbersome and limits the effective working time of the healthcare personnel. For this reason, when adhering SEs to the skin to capture biopotentials, great care must be taken with their position and adherence (Héctor Cruz Enriquez, 2008). Other factors that can alter the quality of the biomedical signal recordings are: the morphology of the person, characteristics of the pathology studied, as well as the configuration of SEs required (Rodríguez Sotelo et al., 2008).

Considering the problems that SEs exhibit, the use of new technologies based on the application of tattoo electrodes (TEs) and the use of flexible electronics has been explored in recent years. There has been growing interest in recent years in the development of non-invasive technologies that allow the design of TEs using flexible electronics. The main objective of TEs is to reduce mechanical stress and to stabilize the acquisition of biomedical signals, thus improving their quality (Wang et al., 2020). TEs have the potential to reduce the drawbacks of SEs and the discomfort of needle electrodes, being able to be used on the skin, adapting to the skin structure, and providing continuous measurements (Rodríguez Sotelo et al., 2008). The advances achieved with the use of TEs has allowed this technology to be used in areas of medicine to measure electrocardiographic, electromyographic activity, temperature, among others, obtaining important results.

The implementation of electronic patches that are able to interact with the human skin and acquire electrophysiological signals can promote digital health, since they would allow wireless data collection in a more comfortable way for the patient (Alberto et al., 2020). With the advancement of medicine, there is an urgent need to incorporate a greater number of portable devices, including those products resulting from flexible electronics (Oh et al., 2020) such as TEs that contribute to the recording of signals of physiological origin.

Based on the above, the present study reviews the state of the art of TEs applications and use, focusing on finding the current challenges and opportunities in this novel technology.

Methodology

The methodology used to carry out this work consisted of a systematic review of articles indexed in the main academic and scientific databases, using as main search engines: PubMed, Google Scholar, Elsevier and SciELO.

The main characteristics for choosing the articles were: (1) studies using flexible electronics and tattoo electronics (2) that the studies have practical biomedical and clinical applications; and (3) the search languages were Spanish and English. The main keywords used were tattoo electrodes, flexible electronics, biocompatibility, electrodes, electrophysiological signals, and COVID-19. Articles that did not relate to the scope of the study of tattoo electrodes and flexible electronics for signal measurement and biomedical signal data were excluded.

Bioelectrical Signals

The human body consists of a large number of cells (De Juan, 2012). When an electrochemical process occurs, cells generate an electrical signal which is transmitted through their cell membrane, and so on, these electrical impulses are converted into an electrical potential that is distributed on the surface of the skin, which is electrically conductive [2].

Cells such as muscle and nerve cells are capable of producing ionic biopotentials (Sörnmo & Laguna, 2005) that can be measured with the use of transducers that are capable of translating this magnitude into electrical current. Electrophysiological measurements are of great importance for medical diagnosis since they can provide relevant information on the physiological functioning of an organ or tissue.

As these cells are capable of being excited, each of them has a specific electrical capacity, where a dysfunction of this capacity can give a diagnosis of the organ's functioning (Enderle & Bronzino, 2012). To measure these bioelectrical signals, study techniques such as:

- Electrocardiography (ECG)

ECG is a method used for the diagnosis and detection of cardiac abnormalities (Martis et al., 2014). The sum of depolarization and repolarization potentials of the cardiac cells of the contractile segments of the heart leads to the electrocardiogram (Enderle & Bronzino, 2012), where by means of the PQRST wave cardiac problems can be detected. This wave provides information on the biopotentials of the membranes that make up the heart (Rabella, 2017), where the P wave is produced due to depolarization of the atria, with an amplitude of 0.1-0.3 mV. It is then followed by the QRS complex corresponding to depolarization of the ventricles with a wave amplitude of 1-1.5 mV, finishing with the T wave given to ventricular repolarization having a wave amplitude of 0.2-0.3 mV (Rabella, 2017).

- Electroencephalography (EEG)

The EEG is responsible for recording all neuronal electrical activity produced by the brain. In this kind of study there is no specific wave pattern since the signal uptake varies greatly depending on the person and the placement of the electrodes. The electrical activity of the brain is visualized through its graphic representation or electroencephalogram. The electroencephalogram is made up of four main waves, which are:

(a) the alpha wave (α) whose frequency oscillates between 8 and 13 Hz; it gives information about occipital relaxation.

b) The beta wave (β) having a frequency of 13 to 30 Hz, it provides information about intense brain activity.

c) The delta wave (δ) has a frequency that oscillates between 0.5 and 4 Hz, it is a normal measurement in children under one year old while sleeping, but in adults this measurement while awake indicates some lesion.

d) The theta wave (θ) frequency is between 4 and 8 Hz, in young sleep state is a normal measurement, this frequency in adults may indicate some brain injury (Rabella, 2017).

- Electromyography (EMG)

EMG can be used to record electrical activity at the muscle level (Sörnmo & Laguna, 2005). This technique is used to evaluate the functional state of muscles during their activation. EMG can be recorded noninvasively by means of electrodes placed on the skin surface, or invasively by means of needle electrodes. The latter requires highly trained personnel.

Conventional Electrodes VS Tattoo Electrodes

TEs are an innovative technological development, demonstrating good performance when recording signals of bioelectrical origin as well as measurement of pH or sweat.

An electrode can be defined simply as a conductive material in contact with a medium, to which it carries or from which it receives an electric current (Enderle & Bronzino, 2012). Its function is to collect the electrical impulses produced by the various cells and transmitted through the skin (Fernández, 2017).

TEs differ from common electrodes, as their technique of use and the material of which they are composed are different. TEs are based on inkjet printing on transferable tattoo paper (Ferrari et al., 2018). In contrast, a common electrode is composed of metallic and rigid materials, which to improve the contact with the skin requires the use of a conductive gel.

As electrodes are essential for capturing electrophysiological signals, they must possess unique characteristics such as good receptivity, i.e. they must have the ability to capture the electrophysiological signals emitted through the skin in an efficient manner (Sörnmo & Laguna, 2005). In addition, TEs must have good skin adaptability and biocompatibility, which is the ability of a material to provide benefits to the receptor organism without causing any harmful damage (Encinas & Cruz, 2018), characteristics that common Ag/AgCl electrodes do not possess (Wu et al., 2021).

The electrodes commonly used in clinical practice to capture physiological signals are surface electrodes, internal electrodes, microelectrodes or stimulation electrodes. Such electrodes are usually composed of metallic materials such as silver, copper, platinum among other materials. Table 1 shows the characteristics of the different types of electrodes currently used for recording bioelectrical signals, including TEs.

Conventional electrodes, although they have many advantages, have limitations in their design which results in a lack of sharpness of the received signal and the stability of the signal varies greatly due to patient movement (L. Zhang et al., 2020).

Table 1
Characteristics of conventional electrodes

Type of electrode	Fabrication	Applications	Advantages	Disadvantages	References
E. Surface acquisition	Silver / Silver Chloride	Measurement of EEG, ECG, and EMG potentials	• No clinical preparation required • No skin damages	• Electrode slippage • Sensitivity to movement • Need a liquid medium for conduction	(Enderle & Bronzino, 2012) (Sörnmo & Laguna, 2005) (Schnyer et al., 2017)
E. internal acquisition	Copper / Platinum	Recording EEG and EMG through the skin	• Better signal recording. • Direct contact with tissues • Low impedance • Good signal to noise ratio	• Invasive • Surgically introduced	(Enderle & Bronzino, 2012) (Sörnmo & Laguna, 2005)

Type of electrode	Fabrication	Applications	Advantages	Disadvantages	References
Microelectrodes	Tungsten / stainless steel / glass	Measurement of electrical potential near and inside cells	• Low Impedance • Long life • Easy to clean • Can be reused	• Difficulty to accurately place inside the cell	(Sörnmo & Laguna, 2005) (Enderle & Bronzino, 2012) (Aragon & Calleja, 2003)
E. Stimulation	Hypoallergenic Hydrogel / Carbon	Pacemakers, functional stimulators, defibrillators	• Support higher currents	• Rapid oxidation due to high current handling	(Sörnmo & Laguna, 2005) (Enderle & Bronzino, 2012)
E. of Tattoo	Silver / Silver Chloride PEDOT: PSS Graphene Polymers	Measurements of ECG, EEG, surface EMG, sweat pH, temperature	• They are flexible • Adapt to the irregular surface of the skin • High mechanical resistance • Good biocompatibility • Portable • Long lasting	• Unstable impedance • Absence of power supply	(Alberto et al., 2020) (Ferrari et al., 2020) (Inzelberg & Hanein, 2019) (Silveira et al., 2021) (Pal et al., 2020)

Table 2
Materials used in the fabrication of tattoo electrodes

Material	Young's module Pa	Conductivity Sm^{-1}	Biocompatibility	Reference
Ag/AgCl	0.74 GPa	0.63 MSm^{-1}	Strong antimicrobial activity	(Roth, 2019) (González Jiménez, 2018)
PEDOT: PSS	1 GPa to 2,7 GPa	1-10 Sm^{-1}	Good skin interconnection	(Lang & Dual, 2007) (Ramírez Quiroz, 2007) (Alberto et al., 2020)
Grafene	1 TPa	0.96 MSm^{-1}	Low cell cytotoxicity For biomedical uses it must be fused with GO films.	(Quiroz Ceballos & Hernández Gervacio, 2015) (Rodríguez Villalón, 2016)
Polymers	0.4 GPa to 2 GPa	Non-conductive	Good interconnection with the skin Can be used in various biomedical applications	(Encinas & Cruz, 2018) (Ferrari et al., 2020)

The implementation of TEs in different electrophysiological studies opens the field to several applications compared to conventional electrodes. Conventional electrodes are uncomfortable due to their rigidity and size, and the type of skin surface greatly affects signal reception, since it is better to use them on flat surfaces than on irregular surfaces. In addition, a wet medium (i.e. conductive gel) must be placed on the electrode when it is used in order to fulfill its function correctly, but as this medium dries the electrode reduces the quality of the recording, and if it has more electrodes close to it, interference may occur (Inzelberg & Hanein, 2019), consequently, a poor signal to noise ratio (SNR) is obtained (Silveira et al., 2021). The presence of noise occurs due to different factors such as the equipment used, the movement of the person or noise of physiological origin (Héctor Cruz Enriquez, 2008).

The main goal in the development of TEs is comfort and no signal loss. In a study, Ferrari et al, found that this type of electrodes can be used in the long term because they resist the flexibility of the skin, adapting to its irregular structure and that hair growth does not damage the tattoo or interfere with signal reception (Ferrari et al., 2018).

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Design Techniques and Materials

An additional main feature that distinguishes TEs from conventional electrodes is the fabrication process and the materials used to develop them, as well as the specific qualities they possess. In recent years, there have been many reports of different application studies in relation to cutaneous electrophysiology. Flexible printed electronics is a manufacturing technology that allows the production of electronic devices and circuits by printing processes on different types of rigid or flexible surfaces (N. L. Cameron, 2006). Thanks to the investigation of new materials, printed electronics is no longer just an experimental technology. Today it can already be considered a reality that opens multiple possibilities.

Flexible electronics applied in living tissues, biomaterials are intended for the manufacture of components, parts or medical devices and systems for application in living beings.

Flexible electronics represents a new window of opportunity for the neuroscientific community, since the development of a chronically stable interconnection with the nervous system may prove this technology to be effective by reducing the immunological reaction of neural tissue (Chen et al., 2021). Although there are still several aspects in which this technology will have to be refined before it can be used clinically, it certainly represents one of the most promising strategies(Chen et al., 2021).

Based on the increasing need to develop noninvasive, easy-to-use, and low-cost diagnostic tools, biomedical devices that can be integrated into human skin have begun to emerge. This "wearable" technology should interface electronics directly to the human skin and detect a variety of biologically relevant signals (Bihar et al., 2018).

The performance of this technology is estimated to be of great importance in personalized medicine for continuous and close monitoring of an individual, because of the benefits it offers in terms of its ability to withstand extreme physical conditions (Gao et al., 2019).

As a device for medical use, TEs must possess specific characteristics such as:

(a) Conductivity: which is the ability to be able to carry and displace electric charge.

b) Elasticity: the electrodes must have the capacity to deform and resist the mechanical stress of movements.

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c) Biocompatibility: the materials used for the manufacture of electrodes is a key point to which much attention must be paid, since the focus of great importance is on electronics compatible with the skin (Salim & Lim, 2019).

d) Softness: this is the property that the electrodes must have to adapt and avoid causing damage to the skin, contributing to the comfort of use (Salim & Lim, 2019).

e) Adhesion: adhesion to the skin must be good, since the adhesive layer is the interface between the electrode and the skin and must be able to adapt to the rough structure of the skin. At the same time, they must allow transpiration, since an excess of water in the contact area can cause interference in the reception of the signal and cause allergies (Wu et al., 2021), (Salim & Lim, 2019).

Three factors are very important for the TEs manufacturing process: (1) to have a Young's modulus (modulus of elasticity) similar or close to that of the skin (1.1 KPa and 20 MPa) (Isaza, 2019), i.e. that allow elasticity without losing its functionality. The closest material to this Young's modulus is the polymers and PEDOT:PSS *(Poly(3,4-ethylenedioxythiophene*) poly(styrene sulfonate)) with a Young's modulus of 0.4 to 2 GPa. (2) Another factor is conductivity. Case in point, silver is a very good conductor having a specific conductivity of 0.63 MSm^{-1}, but because of its stiffness it is used in combination with other flexible materials, but poor conductors. (3) The most important factor is that they possess good biocompatibility with the skin, characteristics described in Table 2. The most commonly used active materials include carbon nanotubes, graphene, silver nanoparticles and PEDOT (Wu et al., 2021).

The implementation of flexible printed electronics is given the use of highly conductive carbon-based aqueous inks. These provide a new option for the commercial application of carbon ink in the field of flexible printed electronics (Liao et al., 2019). In this type of flexible electronic devices, elements such as the substrate (basis for construction), an active layer (including electrical circuits) and an interface layer between them are fundamental (Gao et al., 2019).

One of the most widely used materials for the development of TEs are decal paper nanosheets, whose composition consists of an ethyl cellulose layer and a PEDOT: PSS layer (Zucca et al., 2015). This possesses a good interconnection with the skin, but they have low electrical conductivity.

Furthermore, to reach successful energy harvesting, a combination of good conductivity and low impedance is ideal (Alberto et al., 2020). PEDOT is intrinsically conductive, but has limitations in terms of stretching and possesses poor adhesion (L. Zhang et al., 2020). Materials such as polyimide, polyethylene terephthalate (PET), polyethylene naphthalate, polyurethane, parylene (Pal et al., 2020), are coating materials that are biocompatible. On the other hand, materials such as poly aniline (PANi) present such a low cytotoxicity that the skin irritation and sensitivity it produces is negligible (Windmiller et al., 2013), making it widely used for the development of potentiometric sensors due to its biocompatibility.

Other materials used for the development of these electrodes are the use of piezoelectric polymers such as polyvinylidene fluoride (PVDF) (Ha et al., 2019) and graphene which is used for its extensive properties as an electrical conductor, transparency and its biocompatibility [4].

A great novelty of TE fabrication, in addition to its flexibility and practicality to wear on the skin is that they can be concealed under an artistic tattoo pattern (Windmiller et al., 2013), [45].

TEs are made up of 3 main components which are:

1. The adhesive medium: this is composed of an adhesive layer, a soluble layer (water-soluble polyurethane) and the backing paper. This layer is responsible for allowing the adhesion of the electrode to the skin.

2. The conductive connection: this is the layer that allows electrical conductivity between the electrode and the device that stores the electrophysiological information. This layer uses conductive materials such as silver, graphene, etc. (Table 2).

3. Tattoo electrode: this is the final structure of the printed tattoo with all the layers, ready for implementation on the skin.

Applications of Tattoo Electrodes

TEs offer many advantages and benefits, such as the materials and design with which they are developed, making them more practical for use in different electrophysiological signals studies.

TEs have shown great potential in motion sensing and biosignal measurement applications, which have been beneficial to patients.

Many physiological information is measurable through the surface of the human body using surface electrodes, making the use of tattoo electrodes very innovative for recording different bioelectrical signals.

a) Detection of bioelectrical signals: One of the most measurable physiological parameters is the heart rhythm through the ECG where not only the electrical activity of the heart is measured, but also signals of mechanical and acoustic origin (Ha et al., 2019). When receiving seismo cardiogram (SCG) signals, a stable baseline has been observed at rest, and during voluntary contractions, a wide frequency content is preserved in the EMG (Bandodkar & Windmiller, 2013), with an accurate reproduction of the EMG spectrum over the entire signal bandwidth (Bareket et al., 2016), (Bandodkar et al., 2014). In their study, Inzelberg and Hanein, demonstrated that the use of tattoo electrode arrays is an effective and convenient method to obtain bioelectrical signal recordings with excellent resolution and without interference (Inzelberg & Hanein, 2019). These authors also made use of electrode arrays to obtain EEG, surface EMG and electrooculography (EOG) recordings in sleep disorders, obtaining satisfactory results of long-term measurements.

b) Detection of pH and sodium in sweat: Several advances have been made in the monitoring of electrophysiological signals, including the development of temporary electrodes for sodium uptake in sweat, using ion-selective electrodes (Bandodkar et al., 2014). Their use has made it possible to obtain data on electrolyte loss, noninvasively, using disposable specific ionic concentration (SIC) strips.

The use of portable devices capable of measuring the sodium present in sweat represents a great tool, since they alert the person when he/she has electrolyte loss.

Many of the medical tests utilized to obtain important information about a person's physical well-being are done by blood extraction, which is an invasive technique and does not provide dynamic and continuous information (Pal et al., 2020). Human sweat is a liquid that is very easy to obtain and provides a great deal of chemical information that affects the person. That is why pH measured in sweat is very useful as an indicator of dehydration. Measuring pH is widely used by healthcare professionals to control the balance of different metabolic processes (Salim & Lim, 2019), where its lack of control can lead to physiological disorders such as sepsis, renal failure, among others. For sweat pH measurements, electronic decals and wireless impedance analyzers can be used. Using waterproof electronic decals (WPED), A. Pal et al. implemented the use of biosensors which were able to monitor the pH levels of various fluids (Pal et al., 2020). A clear example was the monitoring of vaginal pH to determine abnormalities leading to bacterial vaginosis (Pal et al., 2020).

Application against COVID-19

The global pandemic of COVID-19 has affected many groups, including healthcare personnel, who are exposed to the virus when performing clinical examinations in which physical contact with patients is necessary for electrophysiological measurements for the diagnosis of different pathologies (Tang et al., 2021).The global pandemic of COVID-19 has affected many groups, among including healthcare personnel, them the who are exposed to the virus when performance of clinical examinations where in which physical contact is with patients is necessary to for perform electrophysiological measurements for the diagnosis of different pathologies (Remuzzi & Remuzzi, 2020), (Tang et al., 2021).

Wireless patient monitoring is a very important tool for home hospitalization, where a person receives medical care at home. A clear example of this type of hospitalization is the one seen during the COVID-19 pandemic, which started in 2020, where many hospitals had to refer their patients home because of reduced capacity (Silva & Tavakoli, 2020). That said, the need for wireless monitoring devices is of utmost importance in events such as this.

Being a new virus, its evolution is under constant study, as for its symptomatology it has been found to produce flu-like symptoms such as dry cough, dyspnea, fatigue, headache and fever (*Coronavirus*, 2021) being the latter symptom one of the most prevalent in these patients (Khalili et al., 2020), Therefore, it is of vital importance to monitor the COVID-19 patients. An innovative and current use given to tattoo electrodes was used by Silveira et al, where with the use of a simple conductor such as aluminum foil and adhesive tape they created a patch capable of measuring body temperature to monitor the febrile state of a COVID-19 positive patient and that the patch had a duration of 72 hours (Silveira et al., 2021).

Discussion

An innovative advance in medicine and electrophysiological signals measurement has been the implementation of TEs. This technology offers interesting advantages compared to conventional electrodes, which are limited by the time and type of study in which they can be used. In addition, many of these electrodes have a rigid structure, which means that they do not fully adhere to the shape of the skin and therefore require other

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elements such as adhesive tapes (Ferrari et al., 2018), making them uncomfortable, and consequently, limiting the patient's freedom of mobility, having as a disadvantage also the effects produced by the use of conductive gels that cause irritation and allergies in users (Wu et al., 2021), (Salim & Lim, 2019). The objective of the use of TEs is to reduce the inherent limitations of conventional surface electrodes inside and outside clinical and hospital environments. Another potential advantage of these devices is that once they become a mature technology, they would save time for healthcare personnel.

The advances demonstrated by flexible printed electronics technology in medicine are groundbreaking. Despite them, it is necessary to emphasize that this technology has certain limitations that condition its use, such as the optimal use of energy, since the batteries used overcome a problem in terms of size compared to the size of an TE (Alberto et al., 2020). These devices are ultra-thin, so the use of small batteries is still a challenge (Bandodkar et al., 2014). On the other hand, most of the studies performed have been in adults, so it is necessary to extend the research to a young and child population, and that in the latter group would be of great help, since, for children, undergoing studies involving the use of classic electrodes can be quite uncomfortable.

As for the portable technologies that currently exist, they face the challenge of being able to perform long-term health monitoring in extreme conditions. External environmental factors involving sudden changes in temperature and humidity can influence the measurement of a device (Niu et al., 2020). These types of flexible electrodes could solve this problem in the future, being able to be used in physically and environmentally extreme conditions (such as high body temperature, heat, sweat, rain, etc.), even allowing them to be washed (H. Zhang et al., 2021).

On the other hand, TEs could be used not only to capture biomedical information but also to transmit it wirelessly via Bluetooth or Wi-Fi to mobile devices such as smartphones, and in this way visualize and remotely send the recorded information (Pineda-López et al., 2018), (Salim & Lim, 2019).

One aspect in favor of TEs is that they have shown a great capacity to resist factors such as bending, stretching and puncture (Bandodkar et al., 2014). In addition, TEs have shown promising results that may enable the crease amplification effect while being highly stretchable (Tang et al., 2021). In addition to the convenience, biocompatibility, and long duration recordings of up to 48 hours of use that can be made (Ferrari et al., 2018), these advantages make TEs attractive candidates not only for recording bioelectrical signals, but also for measuring other parameters such as glucose (Bandodkar et al., 2015), blood pressure, and blood oxygen. These devices would not only make use of biomedical signals, but in turn their applications extend to recording electrochemical signals, and could even be used in the detection of ethyl glucuronide (EtG) in human sweat in breathalyzer tests (Esteban Plaza, 2018).

The potential of ET has been reflected in other important fields such as sports, offering promising applications, mainly for monitoring physical activity and in order to reduce and prevent injuries [51].

It is necessary to emphasize that, although this study has addressed applications with noninvasive recordings, this technology can be used invasively, for the study of intracellular and extracellular bioelectrical signals, and can be implanted inside the body and provide real-time information of vital importance for diagnosis and treatment of complex disorders, as well as improving the design of current implanted devices such as pacemakers (Phan, 2021). Finally, TEs seek to make their way into the field of medicine, as a novel technology of practical but effective use in the recording of biomedical data and signals with the aim of contributing to the progress of medical practice.

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