Flexible Materials and Applications for Wearable Sensors

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Acceptance of Senior Honors Thesis

This Senior Honors Thesis is accepted in partial fulfillment of the requirements for graduation from the Honors Program of Liberty University.

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Abstract

This literature review aimed to address the limitations of rigid wearable sensors in the medical community by investigating the development of flexible materials for remote health monitoring. A keyword search was conducted on Google Scholar, PubMed, and the Jerry Falwell Library, which yielded 9,102 articles. After applying filtering techniques, the results were narrowed down to 21 articles, which were categorized into "Present Market Conditions," "Flexible Materials for Medical Use," "Applications for Wearable Sensors," and "Potential Use Cases." Discussions were held on prominent materials such as substrate, nanocomposite, and liquid metal materials, exploring their potential applications for chemical and physical sensing, as well as power supply considerations for these devices. The study concluded with potential use cases, such as athletic performance metrics, military personnel monitoring, and patients with chronic conditions. The research found that further exploration in the field of soft, textile-based micro batteries is necessary to overcome the current limitations of wearable sensors. The study provides valuable insights into the future of wearable sensors in the medical community and highlights the need for more research into the use of flexible materials.

Flexible Materials and Applications for Wearable Sensors

Introduction

Current wearable devices on the market today are adequate for simple analyses of anatomical health parameters such as heart rate averages and step counters. However, these devices are not capable of making precise measurements of other important health parameters such as blood pressure, respiratory rate, and body temperature. Until wearable devices can perform these measurements, “telehealth” remains improbable.

Background

To discuss the development of wearable sensors for remote health monitoring, it is important to consider the background of wearable devices in general. These devices ranged from pocket-sized earpieces to hearing aids, eventually leading to the widely popular Apple Watch and FitBit.

The first electronic wearable device was developed by a man named Edward Thorp in 1961 (Thorp, 1966). Designed to be worn at the casino, the pocket-sized device could make accurate roulette wheel predictions. While wearing an earpiece to communicate with his accomplice, Thorp realized a gain of 44% - culminating in $8000 worth of total winnings.

While this may have been the first wearable device assembled, it certainly was not the last. The first hearing aids were developed in the 1980’s, and at the turn of the century Bluetooth-enabled devices entered the market (Tjellström & Granström, 1994).

Bluetooth technology allows for dynamic communication between computers within a specified radius, typically less than 20 meters (Zeadally, Siddiqui, & Baig, 2019). Given that consumers tend to keep their cellphones within 20 meters of themselves lends itself to new wearable devices entering the market – such as Bluetooth headsets and earpieces.

The newest and most innovative trends have come more recently, with the development of wearable health devices. The Fitbit released its first step counter in 2008 (Crawford, Lingel, & Karppi, 2015), pioneering the future of wearable technology. In 2011 Fitbits were enabled with an altimeter, digital clock, and a stopwatch – expanding the capabilities of small integrated sensors into a wearable device. Figure 1 demonstrates how other kinds of wearable sensors can be implemented throughout the human body.

Figure 1: Overview of potential wearable sensor locations (Ometov et al., 2021)

Throughout the past decade, simple step counters have evolved into devices that can perform functions previously only accessible in hospitals. A fully-enabled Apple Watch is now capable of tracking heart rate, measuring blood oxygen levels, and generating an electrocardiogram (Avila, 2019) – along with other standard features.

Present Market Conditions

As the market for wearable devices expands, there has been an ever-increasing incentive to develop high-fidelity sensors that can accurately track a variety of critical health parameters in a remote environment. The benefits this technology can bring are widespread, including reduced cost of care, greater access to services, and optimization of clinical staff efficiency. However, current wearable health devices have several barriers that need to be addressed to advance the market.

There are many limitations that these devices face to remain convenient, non-invasive, and accurate. The typical rigid construction of these devices does not lend itself to accurate measurements, and typically requires the use of hospital-grade equipment. Subsequent sections detail the most important health parameters necessary to maintain good health, and the technologies utilized to measure them.

Blood Pressure

The simplest measure of the health of the cardiovascular system is blood pressure – which measures the force of blood pushing against vessel walls. When this pressure is consistently too high, it is a condition known as hypertension. Hypertension is an incredibly difficult condition to track, as it presents very few symptoms (Mills, Stefanescu, & He, 2020), but the consequences are vast and deadly, including heart attack, stroke, aneurysm, and heart failure. The CDC estimates that in 2020, more than 670,000 deaths in the U.S. were attributed to hypertension (CDC, 2023).

With this in mind, it is important to develop reliable methods of tracking blood pressure consistently in order to mitigate the risks associated with hypertension. The primary method of measuring blood pressure is a sphygmomanometer and stethoscope, which is performed with a cuff placed on the patient's upper arm.

There has been little progress on developing methods of conveniently tracking blood pressure in patients via a rigid wrist-worn wearable device. Research into technologies such as pulse transmit time and photoplethysmography has been done by entities such as FitBit and Valencell to try and bridge the gap, but there has been limited success in the ventures (Staff, 2021).

Heart Rate

Heart rate is another important health parameter to measure when determining someone's fitness level. Essentially, heart rate measures exertion level – but there are key insights that can be drawn from heart rate – such as how healthy someone's cardiovascular system is.

Resting heart rate is the rate a heart beats when there is little to no physical exertion occurring. It is an effective measure of the efficiency of the heart: someone whose heart beats 62 times per minute at rest has a much more efficient heart than someone whose heart beats 81 times per minute. Over a lifetime, even subtle differences in resting heart rate leads to massive differences in number of total beats, which is demonstrated in Figure 2.

By the end of their life, for the person whose resting heart rate was 81, their heartbeat is 748,980,000 times more than the person whose resting heart rate was 62. Because of these large differences, it is very important to monitor heart rate to determine if someone is in poor health.

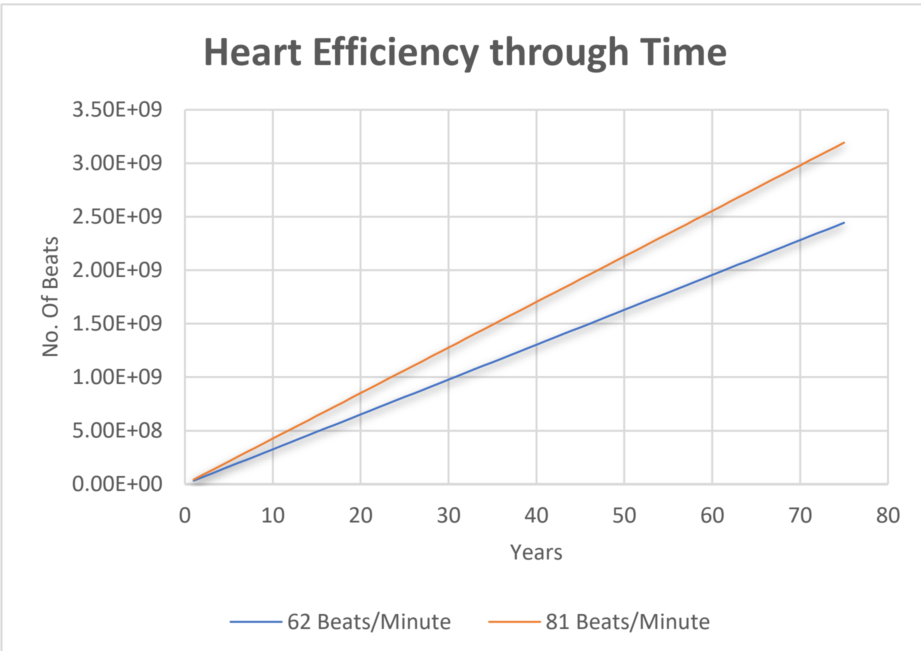

Figure 2: Heart rate efficiency versus time for different beats per minute

Modern wearable devices are capable of measuring heartrate with decent precision. The Apple Watch, for example, has a heart rate monitor that has been deemed safe and effective by the FDA (Hale, 2018), along with the FitBit. However, studies have shown that the Apple Watch's accuracy is less than 50 percent (Aronson, 2020), which is not comparable to hospital-grade equipment.

The Apple Watch tracks heart rate through photoplethysmography (Aronson, 2020). It uses green light to determine the concentration of blood in the bloodstream in regular intervals, determining the rate at which the heart is beating. The FitBit uses similar technology and has a measurement accuracy similar to that of an Apple Watch.

Respiration Rate

Another important health parameter to measure is respiration rate, which is the number of breaths someone takes per minute. For a healthy adult this rate should be between 12 and 20 breaths per minute (Lockett, 2022). Any rate above or below this is considered abnormal. Respiration rate is important to monitor as it can reveal many different health conditions, including asthma, pneumonia, congestive heart failure, lung disease, and drug overdose (Nicolò, Massaroni, Schena, & Sacchetti, 2020).

Like resting heart rate, a lower respiration rate is better than a higher one. It means that the lungs are efficiently oxygenating the body with each breath. When the nervous system is stressed, lungs cannot expand to their full capacity, leading to more breaths per minute, so the body still receives the required amount of oxygenated blood to function (Nicolò, Massaroni, Schena, & Sacchetti, 2020).

Currently, there is a limited market for wearable devices capable of measuring respiration rate. Typical wearable devices are wrist-worn, and there is little data on respiration that can be obtained from this location. Garmin devices claim to have this capability by retrieving data from someone's heart rate variability (HRV) (Garmin, 2020), which is a phenomenon where the time between consecutive heart beats fluctuates from inhalation and exhalation. The scientific term for HRV is respiratory sinus arrhythmia (RSA).

The variability in heart rate caused by RSA can be as small as milliseconds and can only be measured by an exceptionally accurate monitoring device – which should typically be located on the chest to ensure optimal measurements. Because of this, the Garmin device has been found to be inadequate for precise analyses of respiratory rates.

Body Temperature

Throughout the day, it is typical for the human body to fluctuate in body temperature. However, the magnitude of this fluctuation should never exceed 0.5 degrees Celsius, or 0.9 degrees Fahrenheit – with an average temperature of 98.6 degrees Fahrenheit (Del Bene, 1990).

The circumstances for body temperature to increase or decrease at a greater magnitude than specified above are primarily attributed to disease, illness, or other health conditions. There are other instances where these changes can occur as well – such as during exercise or in various stages of a woman's menstrual cycle (Baker, Siboza, & Fuller, 2020). However, the primary reason for body temperature fluctuations is a sign of infection – which is the central motivation for seeking to monitor this vital sign.

There are limited wearable sensors in the market today with the capability of measuring core body temperature accurately and in real-time. This is especially true for wrist-worn sensors that are not proximal to the core of the body.

Companies have developed sensors capable of estimating body temperature near the armpit or even on the torso, such as the CORE sensor and iButton, which was found to be accurate for continuous readings (Hasselberg, McMahon, & Parker, 2010). Currently Garmin, FitBit, and Apple Watch devices are incapable of measuring core body temperature.

Hypothesis

It is apparent that conventional wearable devices are insufficient for measuring precise anatomical parameters. Due to their rigid construction, these devices are incapable of replicating the flexible nature of high-fidelity medical devices. However, there has been increasing research into the efficacy of employing skin-like membranes at various parts of the body to perform noninvasive and highly accurate measurements of most health metrics (Lu et al., 2020).

These devices are seamless, comfortable, and can be capable of transmitting data remotely to off-the-body computers to process and present measurements. Some are made of environmental-friendly materials, making them easy on the environment and human skin. The hypothesis of this literature review is that flexible material based wearable sensors have the potential to replace hospital-grade care in remote locations.

Methods

To determine optimal articles to supplement this literature review, a systematic method was utilized: Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The PRISMA method is valuable to researchers as a method of identifying, including, and excluding articles around a specific topic (Selçuk, 2019). It is broken down into four primary steps: (1) identifying articles for review, (2) screening the articles, (3) deciding on their eligibility, and (4) finalizing the list of articles to include. Figure 3 visualizes this approach.

Subsequent sections detail the identification process for adequate articles, screening procedure for eligibility, and eventual inclusion or exclusion.

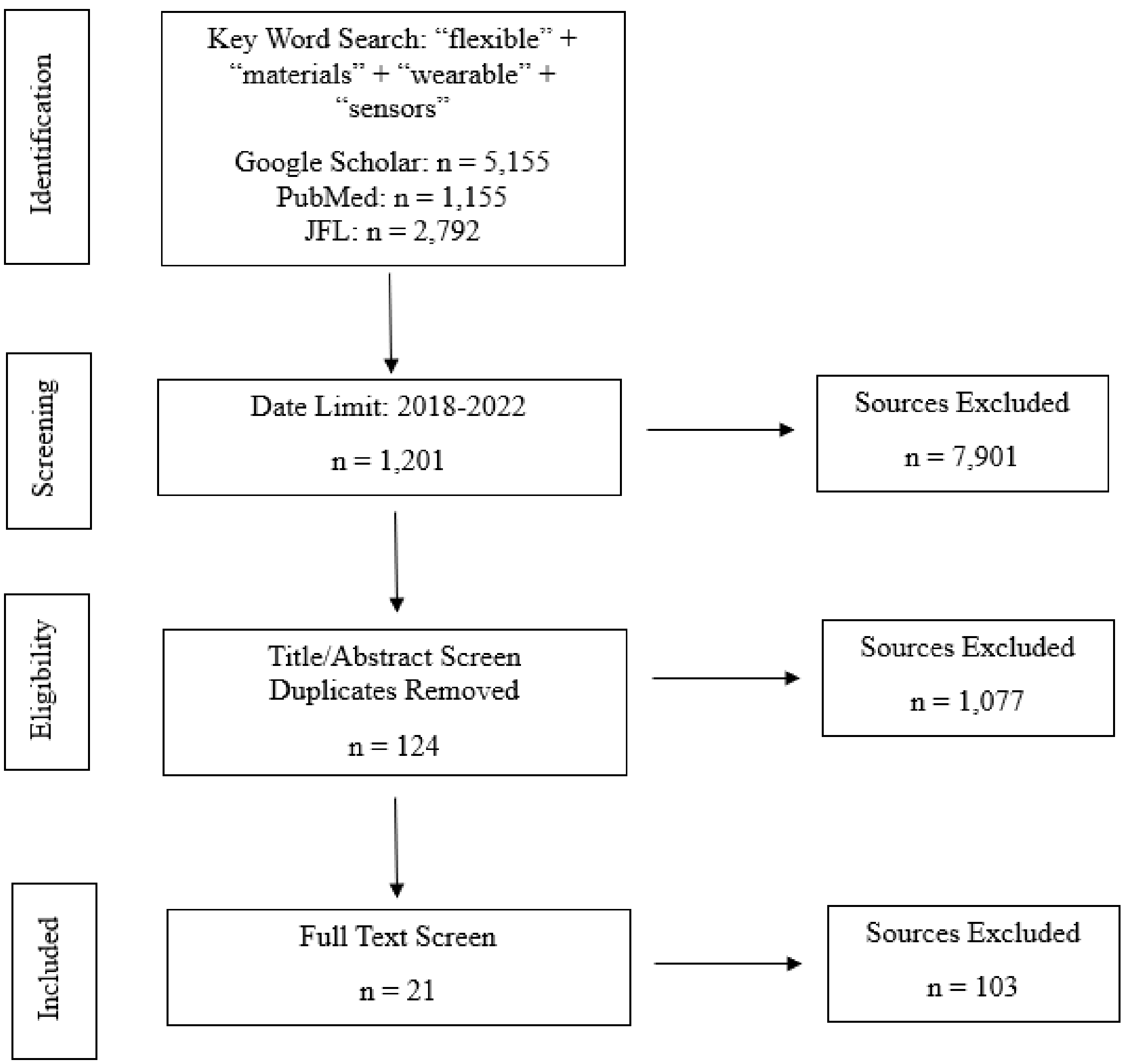

Figure 3: PRISMA flowchart for article selection

Identification

To determine what sources should be included, a keyword search was conducted on several article databases: Google Scholar, PubMed, and Jerry Falwell Library (JFL). The keywords utilized were determined in coordination with Honors department faculty and suggested strategies from related PRISMA reviews: “flexible” + “materials” + “wearable” + “sensors”. Along with keywords, filtering techniques were utilized to determine peer-reviewed journal articles. These keywords yielded 9,102 results, so subsequent filtering techniques were employed to shorten the list of articles for review. The first of these was a date range exclusion from 2018 to 2022. By shortening the length of time to reach back for relevant articles to four years, older research was cut off that does not meet the criteria for innovation. This identification process yielded 1,201 results.

Screening

Following the identification of 1,201 articles related to the topic of flexible materials for wearable sensors, the articles were all screened for their relevance and applicability in this literature review. The screening process consisted of a brief title read to determine if the literature was significant – and was followed by a thorough read-through of the article’s abstract. Duplicate articles across databases were eliminated from consideration. The criteria for eligibility were based on the following research-based characteristics:

- Innovative flexible materials for human-device compatibility
- Power supply considerations for wearable sensors
- Applications of wearable technologies in various industries
- Present and future market applicability

It was determined that this method of screening was sufficient to determine adequate source material for this literature review and resulted in 124 articles eligible for a full-text review.

Eligibility

The full-text review of the 124 articles consisted of a readthrough of the literature's content and an understanding of its findings. The criteria for selection were similar to the screening section of the title and abstract; however, a more arbitrary approach was taken. In collaboration with the Honors department at Liberty University, the content of the articles were studied and determined to be significant or not. A total of 103 articles were excluded following this section of the screening process, leaving 21 articles to be included in this literature review.

Results

Following the systematic review of existing literature, a collection of relevant articles was assembled. The following table outlines the collected articles – identifying them by name, date, category, and a brief description of the topic they researched. A total of 21 articles were collected for review. The four broad categories are as follows, along with a brief summary of each article in Table 1:

1. Present Market Conditions PMC
2. Flexible Materials for Medical Use FMMU
3. Applications for Wearable Sensors AWS
4. Potential-Use Cases PUC

Table 1

No.	Article	Category (s)	Summary
1	(Farmer & Medina, 2020)	FMMU	- Develops a parameter-based dimensionless model applicable to soft actuators

			- Results in a mathematical model capable of describing the motion of double conical dielectric elastomer actuators
2	(Friedl, 2018)	PUC	- Discusses the potential-use cases for wearable sensors in the military to predict real-time physiological status - Could allow for improved casualty detection, chemical threat identification, and detrimental environmental exposures
2	(Gao et al., 2019)	FMMU, AWS	- Reviews existing research into the field of advanced wearable sensors for human body motion detection, temperature, heart rate, respiration rate, blood pressure, pulse oxygenation, and blood glucose - Includes discussions into material considerations, structuring, and production processes
3	(Gao, Ota, Kiriya, Takei, & Javey, 2019)	AWS	- Discusses applications of flexible materials in the wearable sensor market - Identifies key chemical and physical parameters that can be measured by these sensors
4	(Gorski, Mimoto, Khare, Bhatkar, & Combs, 2021)	PUC	- Original research into utilizing wearable heart rate monitors on athletes - Determined that it is feasible to accurately measure and monitor real-time heart rate in athletes
5	(Grisot, Moltubakk Kempton, Hagen, & Aanestad, 2019)	PUC	- Studies how a data-oriented approach to nursing care could enable remote monitoring of patients with chronic conditions - Discusses the importance of nurses to be capable of understanding patient data to improve outcomes
6	(Heng, Yang, Kim, & Xu, 2021)	AWS	- Studies how sweat is one of the most insightful human body characteristics and how measuring it can greatly improve data-driven diagnosis - Discussions are had in the structure and materials of sweat sensors, biological evidence of the significance of sweat-based metrics, and fabrication of sensors
7	(Kang, Park, Kim, & Yu, 2021)	FMMU	- Reviews the field of flexible pressure/tactile sensors based on inorganic and carbon-based materials - Discovers that sensing performance can be significantly improved by enhancing adhesion between the sensor and surface of the target

8	(Kwon, Kim, & Byun, 2019)	PMC	- Researched the validity of the Apple Watch for estimating physical activity in children - Determined that Apple Watch accuracy is limited as compared to Cosmed K5 for measuring time of physical activity
9	(Liu et al., 2018)	FMMU, AWS, PUC	- Comprehensive review of flexible sensors for wearable health monitoring - Discusses sensing mechanisms, materials, fabrication strategies, and features
10	(Lu et al., 2020)	PUC	- Narrative systematic review of existing research into wearable health devices - Covers the potential-use cases of these devices in industry: such as the diagnosis of neurological disorders and rehabilitation treatment in sports
11	(Mirjalali, Peng, Fang, Wang, & Wu, 2022)	PUC	- Discusses how wearable devices can be leveraged to enable early diagnosis of COVID-19 via mechanical, chemical, and biological signals - These sensors are capable of measuring respiration rate, body temperature, and blood oxygen levels remotely
12	(Mondal, Zehra, Choudhury, & Iyer, 2020)	PMC, PUC	- Survey that covers the current state of research in field of wearable sensors, including conventional devices such as the Apple Watch and FitBit - Discusses unique applications of wearable sensors onto a mouthpiece, forehead, and abdomen to measure important health parameters
13	(Muniz-Pardos et al., 2021)	PUC	- Discusses a study of 2020 Olympic athletes where a variety of vital signs were measured to gain insight into performance metrics - Core temperature was measured by ingesting a temperature-sensing pill, and strike angle of foot was measured via an insole pressure sensor
14	(Nasreldin, de Mulatier, Delattre, Ramuz, & Djenizian, 2020)	AWS	- Discusses power supply considerations for wearable sensors, specifically soft micro batteries - Determines that the technology is still in its infancy but that the future market is vast, especially considering the future of wearable electronics
15	(Ometov et al., 2021)	PMC	- A historical survey into wearable sensors and how they have developed throughout history

			- Discusses data transmission technologies, privacy considerations, and hardware constraints
16	(Safaee, Gravely, & Roxbury, 2021)	FMMU	- Studies how reactive oxygen species can be utilized to monitor hydrogen peroxide concentrations in vitro wounds via wearable optical micro fibrous biomaterials - Determines that wearable technologies can detect a wide range of biomolecules including proteins, hormones, and carbohydrates
17	(Shen, 2021)	FMMU, AWS	- Reviews the existing technologies of flexible materials and their applications for surface-worn and implantable biomedical sensors - Concludes that the field of wearable sensors need to advance before the technology can become entirely embraced
18	(Shi, Zhao, Liu, Gao, & Dou, 2019)	PUC	- Discusses the applicability of a body sensor network for military personnel - The proposed framework would cover multiple types of information at a single node: including behaviors, physiology, emotions, fatigue, environments, and locations to enhance information resilience
19	(Su et al., 2020)	FMMU, AWS	- Discusses how wearable, flexible sensors can be employed to measure body temperature - Considers the production of sensors via printing, and how they can be constructed in bulk
20	(Wang, Lou, Jiang, & Shen, 2019)	FMMU, AWS	- Studies the bio-multifunctional nature of specific sensors: biodegradable, self-healing, and biocompatible - These sensors are safe on skin, organs, and most parts of the human body
21	(Yuan & Zhu, 2020)	AWS	- Discusses power supply considerations for wearable technologies via an optimized flexible thermoelectric generator (f-TEG) - Determines the efficacy of utilizing these sensors in a wide range of other wearable applications

Categorized summary of all articles included

Discussion

Following this comprehensive survey of existing literature in the field of flexible materials for wearable sensors a thorough understanding of current technologies was gained. Skin-like materials allow for increased accuracy in human body parameters, and the biodegradable nature of these materials enables safe application on the body. The potential applications of these materials in the wearable sensor market are vast, as they can detect and analyze body positions and excretions such as sweat through chemical and physical means. New considerations into power supply technologies are also becoming more apparent, as textile-based batteries are being developed for seamless operation of wearable sensors without the bulky nature of traditional batteries. This improves human-device synergy, increasing the odds that such technologies will be embraced by the population. Along with knowledge of the present market – insight was gained into how these current technologies can be leveraged in various industries. Examples of these industries are tele-health, athletic performance measuring, and soldier injury monitoring. The subsequent sections further discuss the topics identified throughout this introduction, and how each article contributes to the field of flexible materials for wearable sensing.

Flexible Materials for Medical Use

In order to develop effective flexible wearable sensors, the materials must be identified. There are several categories of these materials that should be considered. Two of which are substrate materials and nanocomposite materials (Gao et al., 2019).

Substrates

The material utilized for the substrate of a wearable sensor is an important consideration. Polydimethylsiloxane (PDMS), Ecoflex, and others do not act as sensors themselves – rather, they act as a matrix into which conductive particles disperse to make sensors. PDMS is a compound widely used in the field of wearable sensors due to its unique characteristics. PDMS is transparent, chemically inert, nonflammable, and non-toxic (Liu et al., 2018). Along with these beneficial chemical characteristics, it is also a very effective mechanical material. An example of its use for a temperature sensor array is demonstrated in Figure 4. However, PDMS tends to perform poorly in thermally stressful environments. Research conducted by Kang has shown that doping carbon materials into silicone elastomers such as PDMS can increase its sheet resistance by several orders of magnitude (Kang, Park, Kim, & Yu, 2021). Other popular substrates include polyurethane, polyethylene terephthalate, polyimide, and Ecoflex (Gao et al., 2019).

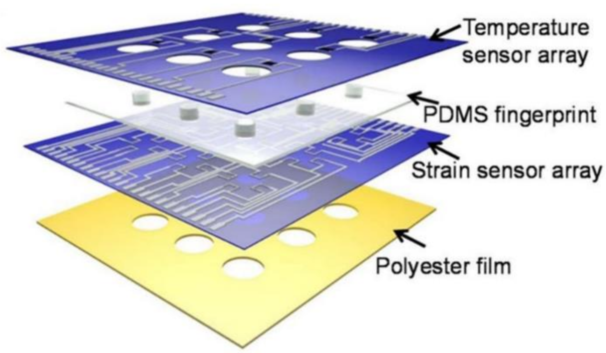

Figure 4: Application of PDMS substrate with temperature sensor array (Su et al., 2020)

Carbon Nanotube

Carbon-based materials have high potential in the flexible materials industry due to their effective electrical conductivity, and improved chemical/mechanical stability over metals (Liu et al., 2018). It has been found that the performance of multi-walled carbon nanotubes versus single-walled carbon nanotubes are not the same (Su et al., 2020). Single-walled carbon nanotubes were found to be more susceptible to electrical conductivity improvements compared to multi-walled carbon nanotubes when encountering the same conditions. Single-walled carbon nanotubes have also been found to be effective at optically monitoring hydrogen peroxide concentrations in vitro wounds (Safaee, Gravely, & Roxbury, 2021).

Bio-Multifunctional Performance

A primary consideration when developing flexible materials for medical use is that it will be compatible with human skin contact externally. Some sensors have even been developed to operate invasively. Because of this, materials should be developed to be bio multifunctional. Research reviewed by Shen describes multifunctional sensors on human skin that respond under different twisting conditions (Shen, 2021). Shen also discusses research conducted on a mice’s cardiovascular system, where a pressure sensor was embedded onto its heart to measure the corresponding electronic signal. These materials are effective but should be improved for sensing stability over long-term body applications.

Applications for Wearable Sensors

The capabilities of the novel materials discussed in the previous section are vast and should be explored more. These capabilities include both chemical and physical sensing of human body movements, and excretions such as sweat. Along with these forms of sensing, considerations have been made to power supply capabilities of existing technologies such as soft micro batteries and textile-based batteries. The overall goal is to ensure human-device synergy between the flexible materials, wearable sensors, and power supply.

Physical Sensing

When it comes to wearable sensors, physical sensing is one of the most insightful measurements that can be made. According to Liu, physical devices measure parameters such as body motions, breath, heart beating, skin temperature, and electrophysiological signals (Liu et al., 2018). Strain and pressure sensors are the primary measurement tool for body motions. Gao reviewed a study that demonstrated that single-walled carbon nanotubes (SWNCTs) deform in a manner that leads to effective strain measurements when utilizing a PDMS substrate (Gao et al., 2019). This experiment was conducted on a knee and effectively measured large-scale movements. Researched reviewed by Shen discussed a humidity sensor capable of measuring respiration rate via a single-crystalline Molybdenum trioxide nanosheet (Shen, 2021). The response speed was very quick (<0.3s) and held a recovery time of <0.5s. There was no noticeable degradation in performance over time. Radial artery pressure sensors are effective for measuring cardiovascular pulse pressure waveforms (Wang, Lou, Jiang, & Shen, 2019). It has been demonstrated that conventional wearables are adequate for low-fidelity measurements of heart rate in wrist worn devices. Body temperature readings are also possible via a graphene oxide active material (Su et al., 2020).

Chemical Sensing

Most wearable sensor research in the field today reports data primarily based on monitoring a user's physical activity. There is a need to develop sensors that can capture molecular data for more insightful health information (Gao, Ota, Kiriya, Takei, & Javey, 2019). One of the key metrics available for researchers is biofluid analysis. By extracting sweat from the human body, insights can be gained into the concentration of lactic acid, alcohol, electrolytes, and pH levels (Liu et al., 2018). Sodium and chloride levels in sweat reflect trans-epidermal water loss from the human body (Heng, Yang, Kim, & Xu, 2021). Figure 5 demonstrates a case where a wearable sweat monitor was utilized to determine the onset time of dehydration. It has also been reported that glucose levels in sweat samples is directly related to blood sugar metabolism – leading researchers to believe that effective monitoring of sweat can be used as an indicator for diabetes (Wang, Lou, Jiang, & Shen, 2019).

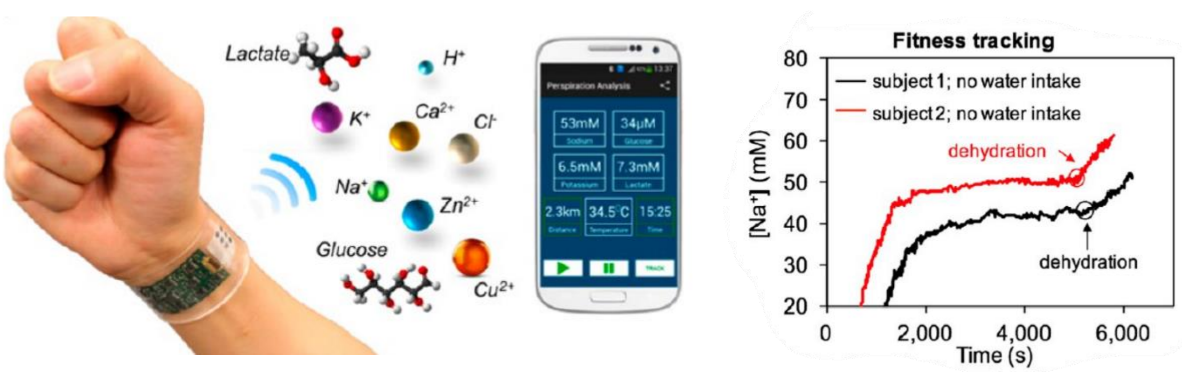

Figure 5: Sweat sensors and resulting dehydration indicators (Gao, Ota, Kiriya, Takei, & Javey, 2019*)*

Power Supply Considerations

An especially important consideration for wearable sensors is power supply. Conventional wearables are rigid in construction, making it possible for rigid batteries to be embedded into their geometry. The development of flexible sensors opens a whole new market for batteries that are soft, flexible, and comfortable. Yuan proposed a flexible thermoelectric generator that is capable of powering a wearable sensor that measures step count, humidity, and temperature (Yuan & Zhu, 2020). The sensor includes an on-board MCU, accelerometer, temperature and humidity sensor, and a simple LCD screen. There has also been a substantial market increase for small-scale flexible micro batteries. Nasreldin reviewed research into a stretchable Lithium-air battery that showed high and stable electrochemical and mechanical performances (Nasreldin, de Mulatier, Delattre, Ramuz, & Djenizian, 2020). When embedded into textiles, the battery performed optimally, demonstrating its unique applications into the field of wearable sensors.

Potential-Use Cases

To highlight the implications of flexible materials for wearable sensors, it is important to document their uses in different industries. Specifically, these include the monitoring of athletic performance, military vital signs, and remote patients with chronic conditions.

Athletic Performance

A study conducted by Gorski researched the efficacy of measuring real-time heart rate metrics of athletes competing on the field using a BioStamp nPoint sensor (Gorski, Mimoto, Khare, Bhatkar, & Combs, 2021). Figure 6 demonstrates a comparison of the BioStamp sensor with the Polar chest strap sensor. Researchers concluded that it is feasible to accurately measure heart rate using the BioStamp sensor. Another study discusses the efficacy of employing a wireless foot insole foot sensor to measure strike angle and contact times of running on a treadmill or running outdoors (Muniz-Pardos et al., 2021).

Another article reviewed the potential for wearable sensors to be utilized in the field of rehabilitation (Lu et al., 2020). The conditions to be rehabilitated could be stroke, brain trauma, spinal cord injury and musculoskeletal injury. A combination of virtual reality, augmented reality, and mixed reality makes such things possible (Lu et al., 2020).

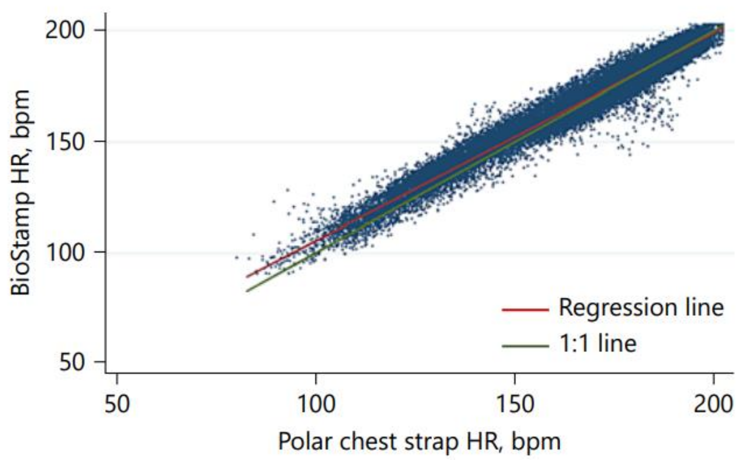

Figure 6: Example of BioStamp heart rate monitor compared to Polar chest strap (Gorski, Mimoto, Khare, Bhatkar, & Combs, 2021)

Soldier Monitoring

Another primary application for flexible materials for wearable sensors is in the military. When in combat, monitoring vital signs is incredibly important. These sensors could be utilized to determine whether a soldier is injured and the manner of injury. Researchers have also determined the need for sensors on bodily extremities to account for hypothermia in soldier's hands and feet (Friedl, 2018). It has also been determined that stress responses can be measured physiologically – including skin conductance and heart rate variability. When a wide array of sensors are employed throughout the body it can be considered a Body Sensor Network (BSN) –

and researchers have determined the efficacy of employing a BSN for soldiers especially (Shi, Zhao, Liu, Gao, & Dou, 2019). This next generation of wearable devices are based on personal attributes of soldiers, improving decision making and information literacy.

Patients with Chronic Conditions

Since the onset of COVID-19, there has been an increasing call for remote care: telehealth. This is primarily due to the overwhelming cost of care in the United States. Wearable sensors provide a new method of monitoring patient conditions that does not require expensive hospital-grade equipment. This is especially prevalent in those with chronic conditions. Research conducted by Grisot demonstrated the importance of data in nursing care and how that data could feasibly be collected (Grisot, Moltubakk Kempton, Hagen, & Aanestad, 2019). With regard to COVID-19 diagnosis – embedded sensors in masks have been demonstrated to effectively identify COVID-19 contamination, along with other diseases.

Conclusion

The field of flexible materials for wearable sensors is a rapidly expanding market. Recent technological advancements are demonstrating the feasibility of these devices in a wide range of industries, including sports medicine, soldier monitoring, and patients with chronic conditions. Traditional wearables are not sufficient to provide accurate measurements of human physiology metrics. This literature review demonstrated that new flexible materials could compete with hospital-grade equipment, supporting the initial hypothesis. Sustained research efforts in this industry should foster significant advancements across the market, leading to increased innovation. These innovations should focus on developing body sensor networks that are financially accessible to the public. By developing sensor networks that are easy-to-use, more data can be collected to determine whether these devices are feasible for remote care applications. Another important aspect for the continued success of wearable sensors is power supply considerations. Preliminary research has shown that soft, textile-based micro batteries are feasible – but more research should be conducted. The potential for flexible materials for wearable sensors is broad, and research and development should continue to enable adaptations across various industries.

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