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Narrative review of the literature: application of mechanical self powered sensors for continuous surveillance of heart functions

Hamza Abu Owida[1], Jamal I. Al-Nabulsi[1], Nidal Turab[2], Muhammad Al-Ayyad[1], Nour Al Hawamdeh[1], Nawaf Alshdaifat[3]
[1]Department of Medical Engineering, Faculty of Engineering, Al-Ahliyya Amman University, Amman, Jordan
[2]Department of Networks and Cyber Security, Faculty of Information Technology, Al-Ahliyya Amman University, Amman, Jordan
[3]Faculty of Information Technology, Applied Science Private University, Amman, Jordan

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ABSTRACT

Cardiovascular disease consistently occupies a prominent position among the leading global causes of mortality. Continuous and real-time monitoring of cardiovascular signs over an extended duration is necessary to identify irregularities and prompt timely intervention. Due to this reason, researchers have invested heavily in developing adaptive sensors that may be worn or implanted and continuously monitor numerous vital physiological characteristics. Mechanical sensors represent a category of devices capable of precisely capturing the temporal variations in pressure within the heart and arteries. Mechanical sensors possess inherent advantages such as exceptional precision and a wide range of adaptability. This article examines four distinct mechanical sensor technologies that rely on capacitive, piezoresistive, piezoelectric, and triboelectric principles. These technologies show great potential as novel approaches for monitoring the cardiovascular system. The subsequent section provides a comprehensive analysis of the biomechanical components of the cardiovascular system, accompanied by an in-depth examination of the methods employed to monitor these intricate systems. These systems measure blood and endocardial pressure, pulse wave, and heart rhythm. Finally, we discuss the potential benefits of continuing health monitoring in vascular disease treatment and the challenges of integrating it into clinical settings.

Corresponding Author:

Nidal Turab
Department of Networks and Cyber Security, Faculty of Information Technology, Al-Ahliyya Amman University
Amman 19328, Jordan
Email: n.turab@ammanu.edu.jo

1. INTRODUCTION

It is widely acknowledged that cardiovascular disease (CVD) and its potential complications are among the leading causes of death worldwide [1]. This figure is projected to increase annually until it reaches 23.6 million by 2030 [2]. The term "cardiovascular disorders" is used to describe a group of abnormal symptoms [3], [4]. All of these conditions are notorious for the devastating toll they take on human life and health, and young adults have taken center stage in recent years [5], [6]. This is because lifestyle factors like being overweight, eating poorly, are major contributors to the development of cardiovascular disease. Preventing most deaths from cardiovascular disease requires early observation, which can lead to timely interventions like improved medication administration and health care delivery [6]–[9]. Heart disease treatment today is a long-term process, but regular check-ups can significantly reduce the likelihood that symptoms will return. CVD can be accurately identified by a variety of imaging techniques used in clinical settings, arteriography, computed tomography (CT), and others [10]–[13].

Therefore, to this day, a major barrier to promoting individualized health care systems has been the lack of inexpensive. Improvements in the accuracy and convenience of pressure sensors designed for use in wearable devices have been notable over the past few decades. Technology advancements have allowed these sensors to be used in a non-invasive, 24/7 capacity for monitoring [14], [15]. Using these biomedical indicators for accurate cardiovascular condition assessment paves the way for a personalized healthcare system with improved health outcomes, ease of use, quality, and cost that is essential for reducing the incidence and mortality rates associated with CVD [11], [13].

A great deal of research has been done on biomechanical devices for detecting [12] to collect physiological data related to the heart. Information reflective can be obtained directly through biomechanical methods by attaching [16]. Because of this, pressure waves can be reflected within the vascular system. To top it all off, they are significantly more efficient because they operate on a power range that typically falls between nanowatts and microwatts. Moreover, additional information about the patient can be inferred from this relationship, which aids in the diagnosis of cardiovascular diseases [11], [17].

This article discusses new heart and lung mechanical sensors. The first section describes four popular mechanical sensors and their functionality. Next, vital sign tracking methods and cardiovascular system physio-mechanical features are discussed. Energy-wise, switching from battery-powered to self-powered sensors are considered. The session concludes with a brief overview of increased cardiovascular system monitoring. The purpose is to safeguard cardiovascular health.

2. BIOMECHANICAL FUNCTION IN THE CARDIOVASCULAR SYSTEM

The biomechanical function in the cardiovascular system involves the mechanical forces and principles that regulate the heart and blood vessels, ensuring efficient blood circulation throughout the body. This includes the dynamics of blood flow (hemodynamics), where the heart generates the force needed to propel blood, and the blood vessels, particularly arteries, manage the pressure and resistance. The elasticity and strength of these vessels are crucial for withstanding and adapting to the continuous mechanical load. Additionally, the heart's ability to contract and relax effectively is essential for maintaining proper circulation, while the structural integrity of the vascular walls is vital for responding to the mechanical stresses of blood flow. Understanding these biomechanical functions is key to addressing cardiovascular health and developing effective medical interventions [18]–[20]. It is normally perceived as a pressure waves. The two most prominent features of a pulse wave are its peak and its trough. As shown by the ascending branch, the artery swells dramatically during ventricular systole, while during ventricular diastole it contracts.

3. SENSING CARDIAC ACTIVITY: THE BASIC CONCEPT

Mechanical methods for monitoring cardiovascular physiological parameters typically employ stretchable sensors like strain sensors and pressure sensors, either implanted or worn by the patient. Figure 1 (see in Appendix) depicts the various basic sensing techniques used by these devices. These include piezoresistive, piezoelectric, triboelectric, and capacitive. The piezoresistive sensor is based on the principle of the piezoresistive effect. The piezoresistive effect describes how the output electrical impulse changes when the pressure on a material that resists electricity changes. Alterations to buildings' electrical resistance due to higher pressure acting on dielectric materials are another method of detection. The resistance of piezoresistive impact sensors is altered when an external force deforms the dielectric material [21]–[25].

4. MONITORING OF CARDIOVASCULAR PHYSIOLOGICAL MEASUREMENTS

Although the physiology of the heart and blood vessels is complex, their primary purpose is clear: to carry oxygen-rich blood to the body's vital organs and tissues. The heart's function as a pump is crucial to this procedure. The term "cardiac cycle" is used to describe the entire sequence of events that takes place between the beginning of one ventricular systole and the beginning of the next. So, it is important to keep an eye on your blood pressure, your heart rate, and other biomechanical processes happening in your cardiovascular system [26], [27].

4.1. Blood pressure

High blood pressure has serious consequences for the cardiovascular system. Since blood is a turbulent, viscous fluid in the aorta's flexible capillaries, most of the energy transfer occurs in the walls of the vessels [28], [29]. Both vasoconstriction and diastole, which affect blood volume, influence the pressure pulsations within the vessels. Auscultatory and oscillometric procedures are the standard in clinical blood pressure measurement. Two methods [18], [19] exist for measuring absolute air pressure, both of which involve inflating a cuff with a compressor and monitoring the resulting gas pressure with a pressure gauge. Assuming that the pressure measured at the brachial artery accurately reflects the pressure at the aortic valve, all that is needed to obtain a person's average blood pressure (BP) reading is a blood pressure cuff measurement. It can't be measured in real time despite being simple to use and low-maintenance. Since real-time monitoring of blood pressure is now possible, the most accurate method of measuring blood pressure is to inject a pressure sensor into the aorta [28]. Nonetheless, this method can't be used for long-term monitoring because of how invasive it is. The cuffless technique [29], which uses a mechanical sensor, allows the patient more freedom of movement.

A triboelectric detector was developed by Fang *et al*. [30] using a functionally resilient textile material. This material is lightweight and can transfer electrical energy from small skin deformations induced by artery pulses. In both active and perspiring states, this allows for the monitoring of pulse waveforms in real-time at a low cost with a high degree of resolution. Using a routine blood pressure gauge, the textile triboelectric sensor supported by machine learning algorithms was put through its paces. It is now possible to share data and conduct data-driven cardiovascular diagnoses because to this technology [31].

A number of cardiac and vascular parameters were non-invasively monitored by Xu *et al*. [32] using self-powered ultrasensitive pulse sensors (SUPSs) placed at several arterial pulse sites. By analyzing the intervals between the peaks of the SUPS pulse waves, they were able to determine the arm-fingertip partial thromboplastin time (PTT). The patient's heart rate, pulse wave velocity, and blood pressure were compared to standard medical equipment using linear fitting to the average value from an electronic cuff blood pressure monitor. The outcomes were consistent.

Weaving pressure sensors that are both flexible and self-powered were developed [33]. Its sensitivity (45.7 mV Pa-1) and response time (less than 5 ms) are all because of its etching Polytetrafluoroethylene (PTFE) into nanowires, which enable it to function with a single electrode. Weight and height measurements were taken from participants ranging in health status from 24 to 82 years old. The PTT was found by subtracting the timestamps of the peaks in the fingertip and ear signal, and the BP measurement was done in real time using an updated genetic algorithm. Discrepancies ranging from 0.87% to 3.65% were recorded between WCSPS and a commercial blood pressure cuff. These things prove that a system for monitoring the heart in real time can be both effective and affordable.

A wireless arterial blood flow monitor that does not require batteries was described by Baoutry *et al*. [34]. The pressure sensor, once assembled, is easy to wrap around arteries of varying sizes because to its lightweight and flexible construction. It is possible to indirectly and directly monitor arterial blood flow using fringe field capacitance technology, which does not require invasive touch. The sensor might be a good option for reducing vascular damage because of its low latency, quick response, cycle stability, longevity, and straightforward, disassembly-free installation.

As part of their vascular electronic system, Herbert *et al*. [35] developed a wireless stent system that uses soft sensors. The sensitivity and response time of the capacitive sensors were improved by aerosol jet printing a patterned dielectric layer and attaching two stretchy connective pressure sensors to the stent. The gadget enables real-time monitoring of blood pressure, heart rate, and blood flow by wireless data transmission through inductive coupling. 3D printing method was developed by Li *et al.* [36] that utilizes an electric field to expedite the in vivo manufacturing of polarized ferroelectric artificial arteries. Without the need for batteries, the arteries can detect obstructions and take real-time blood pressure readings. A polyvinylidene difluoride (PVDF) polymer matrix combined with potassium sodium niobate (KNN) particles produced very high-quality piezoelectric characteristics (d33>12 pC N-1). Because of its 3D printed structure and sinusoidal pattern, the ferroelectric material is able to sense pressure with a mechanical modulus of only 0.306 mV mmHg-1, R2>0.99. of (11.25-225,000 mmHg). Advanced pressure sensors allow for the early detection of even minute changes in blood vessel motion, which aids in the early diagnosis of partial occlusions such as thrombosis and decreases the likelihood of implant failure.

A piezoelectric thin film implanted blood pressure monitor was constructed by Cheng *et al*. [37] without the need for batteries. The output voltage of the sensor was positively correlated with the aortic systolic blood pressure (R2=0.971), and its sensitivity was 14.32 mV mmHg-1. Adult Yorkshire pigs had the polyethylene terephthalate (PETF) implanted so that it could detect the presence of hypertension and activate an alarm. The development of both implanted and external medical devices relies heavily on electromechanical coupling biopolymers. Li and colleagues unveiled the world's first portable thrombus detector in 2019 [38]. Organic piezoelectric nanofibers (OPNs) were synthesized by combining PVDF and KNN in a core/shell structure. These nanofibers exhibit enhanced piezoelectricity, fatigue resistance, stability, and biocompatibility. In order to detect and monitor minute changes in intracellular pressure, a PVDF/HHE OPNs soft sensor was developed. Extremely sensitive and accurate monitoring of micro-pressure variations external to the cardiovascular wall was possible following pig implantation. The piezoelectric signal allows for the detection of elastic changes, thrombus, and atrioventricular heart block. Assessment is facilitated by these biological data.

This facilitates the nucleation of -phase polymer chains and their alignment. The increased piezoelectric properties, biocompatibility, and stability of the developed PVDF/DA NFs are noteworthy. As a result of this study, an all-fiber soft sensor that is both sensitive and accurate in detecting diaphragmatic movement and cardiac blood pulsation has been developed. It can improve treatment by screening for and diagnosing cardiovascular and respiratory problems early on [39]. Twenty-two biosensors Evaluating potential options The -CF2 group on PVDF and the atomic-position NH2 group on DA aid in chain alignment and phase nucleation. The piezoelectric properties of PVDF/DA NFs are enhanced, and they are stable. The results of this study include an all-fiber soft sensor that is both sensitive and accurate enough to detect the diaphragm's movement and the heart's blood pulsing. So, it can be utilized for risk assessment and diagnosis of respiratory and cardiovascular diseases.

With the help of triboelectric nanogenerators (TENG), self-sustaining stents have been developed. A biocompatible, non-toxic, self-sensing stent based on composite mechanical metamaterials was introduced by Barri *et al*. [40]. The hammering of the artery walls could power this stent, allowing it to function independently. A commercial balloon dilator catheter can be used to install the stent while changes in local hemodynamics are evaluated for signs of arterial restenosis or tissue overgrowth. The purpose of this design is only to demonstrate feasibility; its functionality and durability are not priorities. Modern medical stents can incorporate artificial life mechanisms, and this shows how to give smart healthcare systems considerable leeway to do so. Ouyang *et al*. [41] described a pressure sensor in 2021 that uses the triboelectric effect between bioabsorbable materials to instantly transform changes in ambient pressure into electrical data. The linearity (R2=0.993), sensitivity (11 mV mmHg-1), and durability (450,000 cycles) of this bioabsorbable triboelectric sensor (BTS) were above average. Effectiveness in identifying anomalous vascular occlusion in big datasets is high (59.54%).

4.2. Pulse wave and cardiac output

The mechanical pressure sensor can detect and precisely read the pressure signal of a pulse wave because of its exceptional sensitivity and reaction speed. Muscles and elastic connective tissue come together to create arteries. During each cardiac cycle, the ventricle regularly contracts and relaxes, causing a pulse to be transmitted [42]. The electrical activity of the heart determines the pulse rate, which is expressed as a beats per minute (bpm). Current medical wearable electronics makes use of optical and capacitive pulse pressure sensors [12]. Pulse sensors that run on batteries can be optical, piezoresistive, or capacitive. Piezoelectric and triboelectric pressure sensors are examples of pulse detectors that do not require power.

One such device that keeps tabs on vitals in real time is the liquid capsule pressure sensors (LCPS), developed by Fan *et al*. [43]. The liquid inside the capsule is contained by a thin, permeable membrane. By utilizing Pascal's notion, a piezoresistive sensor that was implanted was able to receive the pulsation signal from the capsule. Because of this, the arterial alignment precision of the pressure sensor system was reduced to 8.5 mm. There is a mean correlation coefficient of 0.9944 between the LCPS-derived and electrocardiogram (ECG)-derived heart rates for the 11 persons who wore the device without position calibration. The ECG, photoplethysmography (PPG), and LCPS were used to measure the beat-to-beat systolic and diastolic blood pressure of the subjects, which was then linked with the BP recorded by the cuff. Comparing LCPS+ECG to PPG+ECG, the results demonstrate that both methods are similarly dependable. This easy-to-setup, low-power (35 nW) LCPS delivers a high-fidelity epidermal pulse signal to the sensor. One further way to optimize pulse waveforms is to use a wearable pressure sensor array to measure the spatial and temporal components of pulse waves [43]. Thin sheets of sensitive piezoresistive sensors were manufactured using inkjet by Baek *et al*. [44] to create thin-film transistor (TFT) arrays. Reduced power consumption (101 nW) and enhanced pressure sensitivity (16.8 kPa-1) were achieved through strategic regulation of the TFT operating voltage. A two-dimensional distribution of wrist pulse waves was constructed using a 100-pixel pressure sensor array. A space-time pulse wave map demonstrating the position dependency of pulse amplitude can be generated by precisely measuring the pressure signal and artery position. Because of this, the augmentation index, which evaluates arterial stiffness, can be computed with the right arterial lines. Flexible and sensitive pressure sensors were developed by Su [45]. The sensor's performance was unaffected by the stretching.

Contoured piezoelectric sensors that are gentle on the skin Specifically, lead zirconate titanate (PZT) was utilized by Park *et al*. [46]. A standard method for fabricating tiny, bendable electronics. Then, the thin PZT substrate was affixed with finger electrodes that were forked with gold. The piezoelectric sensors embedded in the wristbands send the pulse values to nearby cellphones in a wireless fashion. Ouyang *et al*. [47] developed a rechargeable ultrasensitive pulse sensor by combining a polymer and nanostructured metallic copper film with an encapsulating layer of flexible polydimethylsiloxane (PDMS) (SUPS) [48]–[51].

4.3. Endocardial pressure and heart rate

Devices such as defibrillators, pacemakers, and cardiorespiratory trainers reduce disease and death by monitoring, restoring, and controlling cardiac function [13], [52]. An important barometer of cardiac pumping is endocardial pressure (EP), which includes both ventricular and atrial pressures [53]. Inadequate external recorders for cardiac catheters might lead to complications during surgery and noncompliance from patients [54]. In practical practice, intermittent EP monitoring has the potential to miss short-lived or quiet symptoms, leading to incorrect patient diagnoses [55].

Active endocardial monitoring and other real-time physiological signal monitoring applications will benefit from self-powered, power-free sensors. Using an i-NG system with flexible and soft nanogenerators, Li *et al*. [56] evaluated the in vivo safety of a cardiac implant. Pigs had i-NGs, leads, and receivers made of piezoelectric PVDF implanted into their hearts over the course of two months. There may be a change due to the diastole PVDF membrane extension. In the event of a heart attack, the peak-to-peak voltage (Vpp) of the i-rapid NG rose from 2.3 to 4.5 V due to the temporary occlusion of the left anterior descending (LAD) artery. In order to track physiological and pathological indicators, Ma *et al.* [57] created an implanted triboelectric active sensor (iTEAS) that is both flexible and self-powered. The triboelectric layer can detach and touch the heart during systole and diastole, creating electrical signals through contact electrification and electrostatic induction, if the cardiac sensor is implanted correctly. Three days following chest closure, the monitor continued to function normally. The device is 99% accurate in its measurement of heart rate. Rhythm abnormalities such premature ventricular beats, ventricular tachycardia, and atrial fibrillation can be identified in real time. The gadget was shown to be biocompatible and ready for clinical usage two weeks following implantation. In healthcare, the suggested iTEAS has the potential to serve as a multifunctional biological monitor that does not require a power supply.

In heart failure, when cardiac function decreases, it is crucial to monitor noninvasive changes in electrocardiogram (EP). The encapsulating layer's compatibility with blood meant that the activation of the coagulation cascade and hemolysis were remote possibilities. By allowing for non-invasive pressure sensing, cardiovascular disease diagnosis, and monitoring, these advancements have the potential to completely transform implanted health monitoring [58], [59].

In their study, Ouyang *et al.* [41] used a large animal model to show that a symbiotic pacemaker based on implanted TENG could harvest energy, store it, and pace the heart. Open circuit voltages of up to 65.2% are possible with implanted TENGs. The endocardial pacing barrier is 0.377 J, which is higher than the energy extraction of 0.495 J during the cardiac cycle. In addition to treating sinus arrhythmias, symbiotic pacemakers slowed the progression of disease. These TENGs are well-suited for use as in vivo synergistic biosensors and other diagnostic and therapeutic applications due to their supercapacitors, endurance, and high coefficient of performance [60]–[62]. Here are the pros and cons of capacitive, piezoresistive, and piezoelectric triboelectric sensors, as shown in Table 1.

Table 1. Characteristics, benefits, and drawbacks of piezoelectric elements triboelectric, conductive, and piezoresistive sensors

Sensor Type	Benefits	Drawbacks
Piezoelectric	Extensive frequency response	Limited to evolving signals
	Extremely sensitive	Emission of current from electric appliances
	Minimalist design that maximizes efficiency	
Piezoresistive	Large dynamic range	Errors caused by elevated temperatures
	Layout and construction that are both straightforward	Intricate production method
	High precision and accuracy	
Capacitive	Significant degree of steadiness	High impedance
	Superb dynamic response	Poor load capacity
Triboelectric	Extremely sensitive	Signals with a high dynamic impedance only
	Layout and construction that are both straightforward	
	Economically viable	

5. CONCLUSION AND FUTURE PROSPECTIVES

Mechanical sensors have the potential to completely transform the way cardiovascular health is assessed through its use. These sensors offer invaluable insights into cardiac function and hemodynamic parameters, paving the way for more accurate diagnostics and proactive management of cardiovascular conditions. The mechanical sensors hold significant promise for enhancing heart-rate monitoring and cardiovascular health assessment. Depending on the specific circumstances and requirements, wearable sensors can be seamlessly integrated into clothing or affixed to the skin using adhesive patches. This non-invasive approach offers unparalleled convenience and excellent patient compliance, making it the preferred option in many cases. Consequently, wearable sensors represent the optimal choice for heart-rate monitoring and cardiovascular assessment due to their ease of use and patient-friendly nature. Conversely, the placement of implantable sensors necessitates invasive surgical procedures, introducing inherent risks and complexities. While implantable sensors may offer certain advantages in specific clinical scenarios, such as continuous monitoring in critically ill patients or those with complex cardiac conditions, their use is often limited by the invasiveness of the implantation process and associated patient discomfort, while both wearable and implantable sensors play crucial roles in cardiovascular health monitoring, wearable sensors emerge as the preferred option for heart-rate monitoring in many situations due to their non-invasive nature and superior patient acceptance. However, the selection of sensor type should be tailored to the individual patient's needs, clinical context, and monitoring objectives, ensuring optimal outcomes and patient satisfaction.

While implantable and wearable pressure devices may incur significant costs, their unparalleled advantages make them indispensable tools, especially for detecting subtle forces within subcutaneous tissue. The primary challenges lie in ensuring the accuracy of measurements and maintaining the functionality of these devices for long-term diagnostic use. While these obstacles are formidable, they are not insurmountable; however, they demand concerted efforts to overcome. Achieving conformal contact with the surfaces of soft tissues and organs represents a critical hurdle that must be addressed to enhance the adaptability and cytocompatibility of sensors. This necessitates further advancements in sensor technology to ensure optimal performance and compatibility with biological tissues. Consequently, there remains a multitude of obstacles to overcome, along with abundant opportunities for growth and optimization in the application of biomechanical sensors for CVD monitoring. Despite the challenges, the potential benefits of overcoming these hurdles are immense, with the prospect of revolutionizing CVD diagnosis and management. With continued innovation and research efforts, biomechanical sensors hold the promise of offering unprecedented insights into cardiovascular health, thereby advancing the forefront of medical technology, and improving patient outcomes in clinical settings. Thus, while the journey ahead may be challenging, the rewards of overcoming these obstacles are boundless.

By integrating energy harvesting and conversion mechanisms, we can actualize a self-charging detection system, effectively reducing the time required to recharge implantable sensors. This innovative approach encompasses both low-energy sensing and self-powered sensing methodologies, offering versatile avenues to accomplish the task at hand. To enable continuous monitoring of multiple physiological parameters. Collaborative efforts among researchers from diverse countries worldwide have spearheaded the development of implantable and wearable sensors. These collaborative endeavors underscore the global significance and potential impact of these sensors as future tools for continuous monitoring of CVD. Scientists from various corners of the globe have united their expertise and resources to design and create these sensors, showcasing the international collaboration and collective commitment to advancing medical technology for improved healthcare outcomes. This collaborative spirit and cross-disciplinary cooperation pave the way for groundbreaking innovations in healthcare, marking a significant stride toward the realization of enhanced diagnostic and monitoring capabilities for managing cardiovascular health on a global scale.

APPENDIX

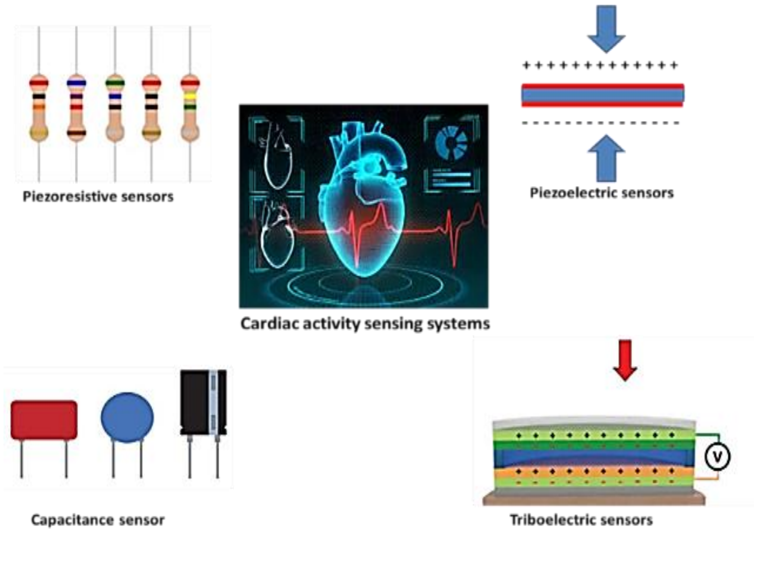

Figure 1. Schematic illustration of different sensing systems for cardiovascular monitoring

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BIOGRAPHIES OF AUTHORS

Hamza Abu Owida holds a Ph.D. in biomedical engineering, assistant professor at the Medical Engineering Department, Al-Ahliyya Amman University, Jordan. Research interests focused on biomedical sensors, nanotechnology, and tissue engineering. He can be contacted by this email: h.abuowida@ammanu.edu.jo.

Jamal I. Al-Nabulsi holds a Ph.D. in biomedical engineering. Professor at the Medical Engineering Department, Al-Ahliyya Amman University, Jordan. His research interests are biomedical sensors, digital signal processing, and image processing. He can be contacted by this email: j.nabulsi@amm.edu.jo.

Nidal Turab holds a Ph.D. in computer science professor at the Networks and Cyber Security Department, Al-Ahliyya Amman University, Jordan. His research interests include WLAN security, computer networks security and cloud computing security, eLearning, and internet of things. He can be contacted at email: N.turab@ammanu.edu.jo.

Muhammad Al-Ayyad holds a Ph.D. in electrical engineering, biomedical instrumentation, associate professor at the Department of Medical Engineering, Al-Ahliyya Amman University, Jordan. His research interests are big home healthcare settings, medical rehabilitation instrumentation, biomedical measurements. He can be contacted at email: mayyad@ammanu.edu.jo.

Nour Al Hawamdeh has completed her bachelor degree from Department of Medical Engineering in Al-Ahliyya Amman University. Her final year project was in application of artificial intelligence for kidney abnormalities detection and classification. She can be contacted at email: Nour.hawamdeh41@gmail.com.

Nawaf Alshdaifat received the B.Sc. degrees in computer science from Al Al-Bayt University and M.Sc. degrees in computer science from the University of Jordan, Jordan, in 2002 and 2011, respectively, and the Ph.D. degree in computer science from Universiti Sains Malaysia, Malaysia, in 2023. His research interests include deep learning and machine learning. He can be contacted at email: n_alshdaifat@asu.edu.jo.