Minimax Theory and its Applications
Volume 11 (2026), No. 3s, 500 to 508

Low Power Electronics Nanosensors in Wearable and Medical Device Applications

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Abstract
This research study provides a methodical summary of the fundamental ideas, significant nanomaterials, cutting-edge production techniques, and many uses of nanosensors in wearable technology. This begins by providing a summary of the convenience benefits that nanosensors offer over traditional wearable technology. After that, it provides a thorough analysis of the nanomaterials currently being used in this field, highlighting their unique properties and drawbacks. The engineering challenges and solutions for large-scale production and device lifetime, including power harvesting and low-power electronics, are also examined in the research[4].The potential for nanosensors to solve the range and understanding issue that predictable sensors face in wearable technology is the reason for the future of nanotechnology in this field. This presents a chance to develop a class of devices that can continuously and accurately collect data. The extremely high surface-to-volume ratio of nanomaterials used in these devices is the primary cause of their numerous performance benefits. This action has improved the biological analytes' ability to communicate, enabling them to identify even minute amounts of biomarkers in physiological fluids including blood, saliva, and perspiration. Such sensitivity is crucial for identifying the minute physiological changes that may point to the presence of a medical condition. The potential for nanosensors to solve the size and sensitivity issues that conventional sensors face in wearable technology is the reason for the future of nanotechnology in this field. This presents a chance to develop a class of devices that can continuously and accurately collect data. The extremely high surface-to-volume ratio of nanomaterials used in these devices is the primary cause of their numerous performance benefits. This action has improved the biological analytes' ability to communicate, enabling them to identify even minute amounts of biomarkers in physiological fluids including blood, saliva, and perspiration. Such sensitivity is crucial for identifying the minute physiological changes that may point to the presence of a medical condition.

Keywords—Electrochemical, Optical, Biosensors, Diagnostics, Data Privacy, Medical

Introduction

The viability of using upper-arm EDA and ECG measurements to identify cognitive stress examines the viability of measuring cognitive stress using electrodermal activity (EDA) and electrocardiogram (ECG) signals obtained at the upper arm. Given the goal of the feasibility research, which was to assess the proposed system's ability to identify changes across conditions, the relatively modest sample size (n = 10) was deliberate [1]. To create controlled levels of cognitive load, an arithmetic procedure comprising four successive stages (relaxation, mild, moderate, and high stress) was employed. Together with self-assessed stress evaluations, physiological

characteristics such as tonic EDA level, tonic slope, number of phasic peaks, heart rate Higher levels of stress were associated with increased physiological activation, as evidenced by the results that demonstrated significant effects of condition for all EDA-derived characteristics and HR. HRV, on the other hand, showed no discernible variations between situations [2]. The most noticeable variations were seen between relaxation and higher stress levels, although the differences between moderate and high stress were less persistent, according to post-hoc analysis. The considerable increase in subjective stress ratings with task difficulty. The results show that the upper arm can offer useful information regarding physiological changes, even if it is not a typical location for such measures. The findings, however, also imply that integrating several physiological cues might be required for a more accurate and thorough assessment of stress.

AuNPs, or gold nanoparticles

Excellent electrical conductivity, minimal toxicity, chemical stability, and biocompatibility Electrical: Conductivity is high; Physical: large surface area, plasmon resonance; chemical: stable drug delivery methods, biosensors, optical nanosensors, and thermoanalysis

AgNPs, or silver nanoparticles

Excellent selectivity, stability, affordability, and high electrical and thermal conductivity Electrical: Of all the metals, the best electrical conductor; Physical: High conductivity of heat Antimicrobial coatings, biosensors, and wound disinfection [3]. High sensitivity and tunable optical characteristics of quantum dots (QDs) Electrical: Semiconductor characteristics; optical: narrow emission spectrum, adjustable emission frequency .Wearable screens, photo resistors, phototransistors, and biological sensing platforms [4]. Although more traditional methods like photolithography are still employed, emerging approaches approaches appear to be more suited to the intricate and adaptable designs required for wearables [5].

Hydrogels, metallic nanomaterials, and carbon-based nanomaterials .Nerve sensors, e-skin, and prosthetic limbs made of nanomaterials. Because of their stability and transmission qualities, carbon-based nanoparticles are being researched extensively for nerve sensors. Elastomers and hydrogels are combined in nanocomposites to produce flexible and sensitive e-skin.

MXene

Wearable sensors with MXene Integration for wireless health monitoring and continuous bio-signal detection Using MXene-based sensors, the research article focuses on creating a versatile wireless system that tracks and logs biosignals produced by human mobility. Superior signal resolution, sensitivity, and stability are provided by the inclusion of MXenes, which improves sensor performance. The suggested system is biocompatible, lightweight, and made for wearable health monitoring. It can record data including joint movement, muscle activity, and heart rate.

When incorporated into flexible substrates, MXene sensors identify mechanical deformations brought on by bodily motions and translate them into electrical impulses. Real-time monitoring and data storage are made possible by a microcontroller that interprets these signals and wirelessly sends them via Wi-Fi to a cloud server or mobile application. Because this technology ensures continuous, real-time monitoring without limiting user movement, it offers considerable advantages in tailored healthcare. The creation of wearable technology based on MXene opens the door to creative, affordable solutions in fitness, rehabilitation, and health monitoring applications, increasing accessibility due to low fabrication costs and raising the standard of medical care.

Nanosensors

The development of multifunctional sensors with flexibility and stretchability, which take advantage of the diverse range of features of organic materials. The development of organic electronic materials has made it possible to construct flexible and elastic organic sensors for wearable applications using a variety of device topologies. This chapter covers a variety of wearable organic nanosensors, including diode-based, electrochemical, resistor-based, and organic field-effect transistor-based sensors. In addition to the four categories of devices listed above, other devices can be made to act as sensors. For example, hollow elastomeric fibers can be used to create soft, flexible capacitive sensors of torsion, strain, and touch. The practical commercialization of smart clothing is anticipated soon, accompanied by further wearable active constituent elements such as a lightweight information processor, stretchable electrical connection, and wearable power source.

Related work

Over ten years have passed since the first mobile device era was introduced. The most recent smart phones and the apps we download from the internet have more recent versions and functionalities. Additionally, with improved features, publishing, music, cinema, television, photography, navigation, banking, and transportation, among other areas, have gotten much smarter [9]. The next generation of technology has arrived and is being worn while attempting to keep up with these advancements. Trackers, smart watches, earbuds, smart apparel, smart jewelry, and more are examples of wearable technology. According to reports, this is one of the newest and fastest-growing technologies in the market. These days, wearable technology is developing more creative solutions. With numerous modern uses, such as illness prevention, health maintenance, weight control, and physical activity monitoring, they play a significant role in the medical industry. Additionally, an embedded SOC (system on chip) is included [10]. The current wearable technology employed in the medical field and the potential for further research into a range of applications are the main topics of this review.

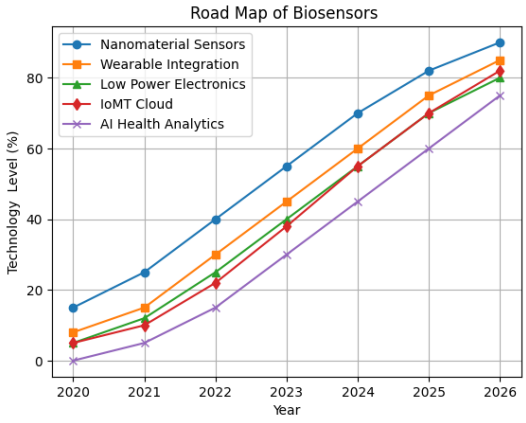


Fig 1. Road map on Medical Device

Personal Parameters in Wearable Technology

A common noninvasive clinical technique for monitoring peripheral oxygen saturation (SpO2), a crucial vital sign, is pulse oximetry. However, research shows that its accuracy is lower in people with darker skin, which frequently leads to concealed hypoxemia. The optical effects of high melanin levels, which obstruct light absorption and transmission, and calibration errors are the causes of this disparity. We suggest a machine learning-based, lightweight correction model that incorporates demographic and skin pigmentation parameters to estimate arterial oxygen saturation from SpO2 values in order to address this discrepancy [13]. We trained and improved a model that can operate in real-time on resource-constrained edge hardware by utilizing the Open Oximetry dataset and compact neural networks. Tensor Flow Lite was used to quantize the model in order to reduce the amount of memory and processing needed. Testing and deployment on a Raspberry Pi 5 verified viability; the quantized model required 43.5 KB of RAM and took 122 ms to infer, yet it achieved an RMSE of 2.103% and an R2 of 0.947. Our method enables demographically informed SpO2 correction on edge devices, indicating a promising route towards bias-aware, accurate oxygen monitoring.

Saline Levels in Healthcare Facilities in Real-Time

For patients with dehydration and other ailments, normal saline therapy is a standard medical procedure. By giving them the fluids and electrolytes their bodies need to function normally, it aids in their recovery. However, in order to prevent any consequences, nurses must pay close attention and monitor the administration of standard saline treatment. Making ensuring that the container's normal saline level doesn't fall below a predetermined threshold is one of the main challenges. Patients may experience severe consequences if staff members are careless and fail to detect when the container's supply of normal saline runs out.

The reason for this is that when there is no more normal saline fluid, the blood may return to the container, forming air bubbles that may obstruct the blood arteries and result in an embolism. An Internet of Things (IoT)-based system for monitoring normal saline levels has been developed to avoid this. Using sensors affixed to the container and the patient's arm, the suggested system keeps an eye on and controls the typical saline flow. The amount of regular saline fluid in the container is indicated by its weight. Once the fluid level drops below a predetermined threshold, a solenoid valve stops the flow of regular saline fluid. The system also has additional

sensors to assess the patient's blood pressure and pulse rate.

When the patient's vital signs deviate from normal and the normal saline fluid level reaches predetermined levels, the system notifies the caretakers through a web site or a mobile app. This suggested method uses a strain gauge kind of load cell, which offers ±0.1% weight accuracy. In particular, during busy times or night shifts when nurses may have several patients to attend to, this suggested technique can increase patient safety and lower the possibility of mistakes.

Remote Patient Health Monitoring with MediConnect

Create a health monitoring system based on the Internet of Things. Assure Bluetooth and Wi-Fi data transmission in real-time.Turn on early health alarms. Wearable biosensors are used by the system to track health data, which is then sent to mobile devices or cloud platforms via Bluetooth or Wi-Fi for real-time analysis and alarms. -Affordable options for widespread adoption.Wearable battery efficiency.

Data security issues the smart health monitoring system continue to keep an eye on critical health indicators, such as body temperature, blood sugar, and heart rate. Make it possible to identify health problems early. Make it easier to check health remotely for improved patient care. Sensors with Arduino microcontrollers are used by the system to gather health data, which is then sent to Thing Speak for remote monitoring and alarms via ESP8266.
A more accurate sensor. Inexpensive fixes. Improved security and privacy of data. A better integration of glucose monitoring. Systems' adaptability and scalability

Wearable Technology and Issues

Group wearable technology according to its use and functionality. Tackle issues with computation, energy efficiency, and communication security. Examine potential avenues for wearable technologies. Researched topics like data security and energy efficiency, compared wearable specs, examined research materials, and surveyed more than 100 items. Limited wearable interaction. Inadequate platforms for managing devices .Inadequate power optimization and security in networks with several devices. -Little research on wearables that run on their own power for ongoing surveillance

Proposed Methodology

Developments in Power Management, Energy Harvesting, and Battery Life to Facilitate Extended Use Technologies for Harvesting Energy Biofuel cells (BFCs) provide continuous power for extended periods of time using natural fuels like glucose or perspiration. By converting motion into power, piezoelectric and triboelectric nanogenerators lessen the requirement for recharging. Fig 1 innovations in energy storage and low-power designs increase the longevity and effectiveness of devices. Smart contact lenses and other self-powered wearables use body energy to reduce the need for external charge, making them more convenient.

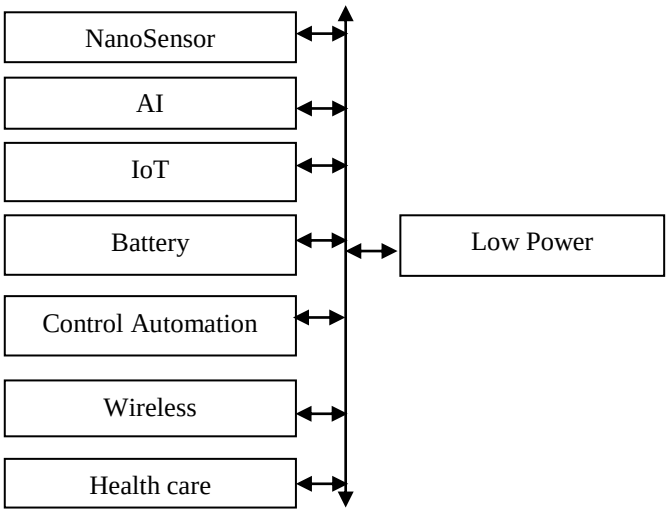


Fig. 1. Block diagram

Health care

Multimodal physiological signal analysis for healthcare stress, fatigue, and cognitive load monitoring in order to obtain consistent and reliable monitoring of stress, tiredness, and cognitive load in clinical settings, the suggested conceptual paper offers a rational and integrated system of multimodal analysis of physiological signals. In contrast to the current approaches that seek to measure the biosignals independently or only predict a single outcome, the proposed framework is a comprehensive merger of heterogeneous physiological streams such as electrodermal activity, photoplethysmography, breathing responses, eye-tracking measures, and brainwave responses to obtain a single cognitive-affective state model. The method emphasizes context-adaptive feature extraction, semantic signal correspondence, and correlating reasoning across modalities rather than the typical sensor level fusion. In order to anticipate patients' and healthcare professionals' mental and physical overload in advance, a hierarchical representation model is explained to explain both small and long-standing behavioral tendencies. The clinical usability and scalability, the framework also conceptualizes zero-intrusion sensing, ethical data governance, and customizable parameter calibration. The basic template for next-generation human-centered monitoring systems that can prevent medical errors, enhance wellbeing in complex healthcare procedures, and facilitate decision-making.

Physiological activation

The intelligent connected vehicle cognitive-informed car-following method taking driver physiological activation into account Though most current designs ignore the driver's psychological impression of car-following safety, longitudinal control systems in intelligent connected vehicles (ICVs) greatly minimize driving workload. This disregard can increase physiological stress and undermine systemic trust. This research suggests a human-centered Connected Adaptive Cruise Control (C-ACC) approach that incorporates the driver's personalized cognitive safety assessments into the control loop in a networked setting. We create a customized safety limit in the speed-distance domain using naturalistic driving data that simultaneously capture vehicle statuses, driver physiology, and traffic environment. The boundary is included as a soft constraint in a Model Predictive Control (MPC) framework and is parameterized by a Sigmoid function fitted to physiological activation features. Most importantly, the controller uses Vehicle-to-Vehicle (V2V) communication to maximize tracking performance and prevent conditions linked to high activation. Two genuine automobiles equipped with V2V communication were used in driver-in-the-loop studies to validate the method. The results of the experiment show that, when compared to baseline tactics, the suggested method successfully lowers psychological stress and physiological activity while maintaining ride comfort and control stability, improving the driver's perception of safety and trust. Most importantly, the controller uses Vehicle-to-Vehicle (V2V) communication to maximize tracking performance and prevent conditions linked to high activation. Two genuine automobiles equipped with V2V communication were used in driver-in-the-loop studies to validate the method. The results of the experiment show that, when compared to baseline tactics, the suggested method successfully lowers psychological stress and physiological activity while maintaining ride comfort and control stability, improving the driver's perception of safety and trust.

Psychological stress

Machine learning-based bioinformatics-driven biostatistical pathway framework for predicting athlete burnout on physiological signals multimodal the complex interaction of physiological load, psychological stress, and recovery imbalance results in athlete burnout, a multifactorial syndrome. In order to model burnout risk utilizing physiological and behavioral data, this study suggests a biostatistical route framework powered by bioinformatics combined with a Multimodal Machine Learning (MML) pipeline. In order to provide interpretable structure, decreased dimensionality, and hypothesis-driven comparisons, raw features were organized into domain-specific pathways (such as cardiovascular load, sleep regulation, movement variability, and autonomic indicators), drawing inspiration from omics analytics. Discriminative markers linked to a higher risk of burnout were found using biostatistical modeling, which included normality testing, effect-size analysis, and pathway-level hypothesis testing. Gradient-boosting models and cross-validated hyperparameter tuning were used to include multimodal features into a supervised learning pipeline. Each physiological component's burnout risk was assessed using explainability (SHAP important ratings and pathway-level contribution indices). We discovered that pathway-structured fusion offers interpretable insights into fatigue-related phenomena and performs better than flat feature models in predicting burnout states. An interpretable and data-efficient system for tracking burnout in high-performance athletes is developed using bioinformatics, biostatistics, and sports analytics. Multimodal health-performance modeling can use this approach.

Physiological and biological signals

The identifying emotions from physiological reactions: usability and accessibility of publicly accessible datasets emotion recognition using physiological and biological signals provides valuable complementary information for clinical monitoring, symptom assessment, and the evaluation of affective states, although it is not intended to serve as a standalone diagnostic tool. Despite its growing importance, the usability of existing emotion recognition datasets is often limited by issues related to accessibility, licensing restrictions, and the insufficient inclusion of neutral emotional stimuli. Current datasets are generally designed either for training artificial intelligence models or for eliciting emotional responses, both of which play a vital role in advancing emotion recognition research. This review presents a systematic analysis of publicly available emotion recognition datasets and provides recommendations for improving their quality and usability. Following the PRISMA methodology, six scientific databases were searched using predefined keywords, resulting in 2,679 records, of which 43 studies met the inclusion criteria after the screening process. The selected datasets were evaluated based on four key aspects: the availability of neutral stimuli, dataset accessibility, commercial licensing permissions, and emotion assessment methodologies. The review covers datasets containing visual, auditory, physiological, and multimodal data, with their relevance determined through methodological quality assessment. The findings reveal several limitations, including restricted access for non-academic users, inconsistent incorporation of neutral emotional states, and variations in emotion annotation methods.

Blood Glucose

Blood glucose prediction effective management of category 1 diabetes. Although deep learning-based multivariate glucose prediction models can achieve high accuracy, they may learn incorrect relationships from raw training data that do not represent true physiological glucose dynamics. Such inaccurate learning can result in unreliable and potentially unsafe predictions in real-world applications. Previous approaches using physiological metabolic equation-based transformations have helped deep learning models generate more biologically consistent predictions, but they have limitations in handling variations between individual patients. To overcome these challenges, this study introduces the Physiological Recurrent Unit (PRU), a novel module designed to improve glucose prediction by incorporating physiological knowledge into deep learning models. The PRU enhances feature learning by guiding models toward physiologically meaningful relationships and can be easily integrated with existing neural network architectures for end-to-end training. Personalized physiological parameters are optimized through gradient-based learning to capture individual differences among patients. Experimental evaluation using the real-world OhioT1DM dataset shows that the proposed PRU combined with a Gated Recurrent Unit (GRU) model achieves superior blood glucose prediction performance, particularly for a 30-minute prediction horizon. This approach improves the reliability and personalization of glucose monitoring systems, supporting better diabetes management and decision-making.

Result And Discussion

Wearable Biosensor Applications And Difficulties In Healthcare.

Improved patient care IoT and wearable medical technology give patients and healthcare professionals real-time feedback. Through telehealth and remote monitoring, it encourages prompt medical treatments and proactive health management. Improves healthcare efficiency and cuts down on needless medical services.Wearable Vital Sign monitoring devices cutting-edge wearables use several biosensors to track variables including blood sugar, temperature, and heart rate.

Wearable Non-Invasive Sensor

Falls among older adults in crowded public environments are a major safety concern because conventional camera-based monitoring systems face limitations related to privacy issues and visual obstructions. Existing wearable fall detection devices mainly identify falls after they occur, which reduces the opportunity for injury prevention, and they may generate false alarms due to accidental impacts or disturbances in crowded areas. It integrates congestion mitigation techniques with fault-tolerant algorithms. In order to efficiently disperse packets and flits and steer clear of crowded and problematic areas, the suggested method makes use of a double-sensing system. In comparison to current methods, simulation results show that the suggested approach improves system resiliency and sustains performance under different fault rates and traffic patterns. In high fault circumstances, the method ensures minimal complexity while achieving lower latency and higher throughput.

In response to the need for high-performance, economical wireless connectivity, this letter suggests a Stackelberg game-theoretic framework for intelligent network selection in hybrid RF–VLC systems. In contrast

to traditional static allocation systems, the framework allows for dynamic decision-making in which customers, as followers, choose networks to maximize multi-dimensional utility functions while network providers, acting as leaders, optimize price, bandwidth, and transmission power. The method balances provider goals of revenue and load distribution while taking into account data throughput, latency, energy efficiency, and user reliability. To accurately estimate SNR and throughput, channel modeling use the Lambertian model for VLC and log-distance path loss for RF. The framework's scalability, interpretability, and computational efficiency over purely learning-based approaches are highlighted by simulation results, which show significant improvements in network efficiency, load balancing, and user satisfaction.

The development of advanced digital ecosystems is driving the vision of next-generation networks toward higher levels of intelligence, adaptability, and automation. Future 6G networks are expected to support key capabilities such as native Artificial Intelligence (AI) integration, cognitive network architectures, ultra-low latency communication, massive connectivity, and self-optimization. Achieving these capabilities requires intelligent algorithms and advanced enabling technologies that can automatically analyze, predict, and optimize network operations.

Experimental

1) Methods Wearable Biosensors

To provides information on the many kinds of biosensors, their techniques, and their outcomes. Electrochemical Transform chemical energy into electrical impulses to identify biochemical reactions. Usually employed to quantify particular ions or compounds in physiological fluids such as blood or sweat. Sweat sensors, electrolyte monitoring patches, and continuous glucose monitors (CGM) constant observation of sodium, lactate, and glucose levels. beneficial for managing long-term conditions like diabetes. Dexcom CGM and Freestyle Libre Optical Utilize methods like fluorescence or infrared spectroscopy to evaluate physiological factors and use light to identify biomolecular interactions.

Skin analyzers, pulse oximeters, fitness trackers, and smart watches non-invasive assessments of heart rate, pulse rate, and oxygen saturation (SpO_2). provide info in real time.

Wearable stress monitors, pathogen detection patches, and respiration monitors .Keep an eye on stress levels, respiratory metrics, and early indicators of illnesses or infections. Respiratory piezoelectric monitors.Heat Identify temperature variations brought on by enzyme activity, fever, metabolic activities, or biochemical reactions.
Drug efficacy monitors, fever detection patches, and metabolic trackers .Keep an eye on your body's temperature and metabolism. Identify early indicators of fever or altered metabolism in athletes. Thermochron sensors and Temp Impedimetric Determine how biochemical interactions affect tissues' or fluids' impedance (resistance and reactance).

Skin conductance sensors, wound monitoring bandages, and smart textiles Assess biomarkers, skin conductivity, and moisture. Examine tissue health or look for microbial diseases. Wearables with bioimpedance capabilities and bandages for wound monitoring.

Physiological Monitoring

Remote Physiological Monitoring (RPM) using visual data has become an emerging healthcare technology that enables non-contact monitor of essential signs such as heart rate .This survey presents a structured review of RPM techniques using a four-axis taxonomy and analyzes eight publicly available benchmark datasets along with representative deep learning approaches .The study covers traditional signal processing methods, advanced deep learning architectures, and multimodal fusion techniques, focusing on how different design strategies improve robustness against challenges such as motion interference, lighting variations, and individual physiological differences. The survey also explores existing gaps in multimodal integration, evaluation standards, and model generalization across different datasets and real-world environments. Recent approaches, including DiffPhys and RhythmFormer, demonstrate promising results; however, they still require large-scale cross-dataset validation to confirm their reliability. The review critically examines available datasets, evaluation protocols, and performance metrics while identifying major limitations in current RPM research. Since standardized large-scale comparisons across multiple datasets remain limited, this work provides a comprehensive conceptual analysis based on existing studies rather than a formal statistical meta-analysis. Finally, the survey highlights future research challenges related to model generalization, computational efficiency, interpretability, privacy, and ethical considerations, providing directions for developing more reliable

and practical visual-based physiological monitoring systems.

This paper introduces Resonant, a web-based Extended Reality (XR) platform designed to capture, share, and represent cardiac signals through haptic feedback using virtual reality headsets and mobile devices. The system combines multiple sensing approaches, including headset-based ballistocardiography, mobile remote photoplethysmography (rPPG), and commercial heart rate monitoring devices for performance validation and comparison. Unlike traditional heart monitoring systems that require external sensors, Resonant enables heart rate measurement directly through XR devices while providing synchronized haptic feedback based on cardiac activity. The main objective of the platform is to support physiological signal sharing without the need for specialized monitoring equipment, enabling new XR experiences that enhance social interaction and emotional connection. This study presents the overall system architecture, sensing techniques, and a workflow for synchronizing heartbeat-based haptic feedback with digital narrative content. Although the potential psychological and physiological impacts of the system require further investigation, Resonant provides a foundation for future XR applications involving shared physiological experiences and human connection.

Conclusion

Wearable technology has been used for several tasks during the last ten years, such as taking calls and keeping track of steps. By adding sensors to these gadgets, technological advancements have made it possible to measure vital signs. As a result, these gadgets can be used to remotely check on patients' health. In this research, we suggest a framework that would enable doctors to keep an eye on some of their patients' vital signs from a distance. The proposed framework protects patient privacy by giving the patient total control over what a doctor can see. Numerous disorders can be identified using the gathered data.

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