Uluslararası Avrasya Sosyal Bilimler Dergisi / *The International Journal of Eurasia Social Sciences*
Cilt/Volume: 16, Sayı/No: 60, Yıl/Year: 2025, ss. / pp.: 1002-1028
E-ISSN: 2146-1961
URL: https://rrpubs.com/index.php/ijoess

Applications of wearable sensor technology for health monitoring in sports: Laboratory setup and requirements and future perspectives

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Araştırma Makalesi/*Research Article*		**DOI:** 10.70736/ijoess.1663
Gönderi Tarihi/ *Received:* 16.09.2024	Kabul Tarih/ *Accepted:* 04.06.2025	Online Yayın Tarihi/ *Published*: 15.06.2025

Abstract

Wearable sensor technology is at the forefront of innovation, transforming health monitoring and sports sciences with its ability to collect and analyze real-time data. These sensors, integrated seamlessly into clothing, accessories, or skin-like patches, enable non-invasive tracking of physiological parameters such as heart rate, body temperature, and movement patterns. For athletes, this data provides actionable insights to optimize performance, prevent injuries, and support recovery. Beyond individual health, wearable sensors are pivotal in structural health monitoring (SHM), where they ensure the safety and functionality of large sports facilities by detecting stress, vibrations, and early structural weaknesses. Driven by advancements in digitization, wireless technologies, recycled materials, and emerging quantum materials, wearable sensors have undergone significant evolution through enhanced manufacturing processes such as 3D printing. This dual application in human health and structural integrity highlights their critical role in creating safer, smarter, and more sustainable environments. This study explores the transformative potential of wearable sensors in sports sciences and structural monitoring, emphasizing their use in optimizing athlete health and maintaining infrastructure safety. Additionally, it examines the infrastructure and equipment requirements for establishing a cutting-edge wearable sensor research laboratory in a university setting. By bridging human well-being and structural reliability, wearable sensor technology advances not only health and performance but also innovation and sustainability, marking it as a cornerstone for future progress in sports and health sciences.

Keywords: 3D Printing, Health monitoring, Sports Science, Structural Health Monitoring (SHM), Wearable sensors

Sporlarda sağlık izleme için giyilebilir sensör teknolojisinin uygulamaları: Laboratuvar kurulumu ve gereksinimleri ve gelecek perspektifleri

Özet

Giyilebilir sensör teknolojisi, gerçek zamanlı verileri toplama ve analiz etme yeteneğiyle sağlık izleme ve spor bilimlerini dönüştürerek inovasyonun ön saflarında yer almaktadır. Giysilere, aksesuarlara veya cilt benzeri yamalara kusursuz bir şekilde entegre edilen bu sensörler, kalp atış hızı, vücut sıcaklığı ve hareket kalıpları gibi fizyolojik parametrelerin invaziv olmayan bir şekilde izlenmesini sağlar. Sporcular için bu veriler, performansı optimize etmek, yaralanmaları önlemek ve iyileşmeyi desteklemek için eyleme geçirilebilir içgörüler sağlar. Bireysel sağlığın ötesinde, giyilebilir sensörler yapısal sağlık izlemede (SHM) çok önemlidir; burada stresi, titreşimleri ve erken yapısal zayıflıkları tespit ederek büyük spor tesislerinin güvenliğini ve işlevselliğini sağlarlar. Dijitalleşme, kablosuz teknolojiler, geri dönüştürülmüş malzemeler ve ortaya çıkan kuantum malzemelerdeki gelişmelerle yönlendirilen giyilebilir sensörler, 3D baskı gibi gelişmiş üretim süreçleri aracılığıyla önemli bir evrim geçirdi. İnsan sağlığı ve yapısal bütünlükteki bu ikili uygulama, daha güvenli, daha akıllı ve daha sürdürülebilir ortamlar yaratmadaki kritik rollerini vurgulamaktadır. Bu çalışma, giyilebilir sensörlerin spor bilimleri ve yapısal izlemedeki dönüştürücü potansiyelini araştırarak, sporcu sağlığını optimize etmede ve altyapı güvenliğini sağlamada kullanımlarını vurgulamaktadır. Ayrıca, bir üniversite ortamında son teknoloji ürünü bir giyilebilir sensör araştırma laboratuvarı kurmak için altyapı ve ekipman gereksinimlerini incelemektedir. İnsan refahı ve yapısal güvenilirlik arasında köprü kurarak, giyilebilir sensör teknolojisi yalnızca sağlık ve performansı değil aynı zamanda inovasyonu ve sürdürülebilirliği de ilerletmekte ve onu spor ve sağlık bilimlerinde gelecekteki ilerlemenin temel taşı olarak işaretlemektedir.

Anahtar Kelimeler: *3D Baskı, Sağlık izleme, Spor Bilimi, Yapısal Sağlık İzleme (SHM), Giyilebilir sensörler*

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INTRODUCTION

Wearable sensor technology has emerged as a transformative innovation, driving progress across various industries, particularly in sports sciences and structural monitoring. At its essence, a sensor is a highly sophisticated device capable of detecting and measuring changes in physical, chemical, or biological conditions, converting these variations into actionable electrical signals for analysis (Kumar et al., 2021). In the context of sports and sports-related environments, sensors have become indispensable, providing critical insights into human health and the structural integrity of facilities.

The healthy human body, particularly that of athletes, serves as a dynamic reference point and testing ground for wearable sensors. These sensors, seamlessly integrated into clothing, accessories, or skin-like patches, provide real-time, non-invasive monitoring of essential physiological parameters, such as heart rate, oxygen saturation, body temperature, and movement patterns (Yang, 2024; Lv, 2024). This continuous flow of data empowers athletes and coaches to make informed decisions, optimizing training regimens and recovery strategies while minimizing risks like dehydration, overexertion, or injury. The human body, with its complex and adaptive systems, offers an ideal benchmark for calibrating these sensors, ensuring they perform reliably in diverse and demanding conditions.

Similarly, large, crowded structures such as stadiums and arenas serve as critical environments for testing structural health monitoring (SHM) sensors (Lucà et al., 2024). These spaces are subjected to constant stress, vibrations, and environmental changes, particularly during large-scale events. SHM sensors embedded within these structures monitor wear and tear, detect stress points, and provide early warnings of potential failures, ensuring the safety of thousands of occupants. These real-world applications refine sensor performance, making them more accurate, reliable, and adaptable to complex environments.

Driven by advancements in digitization, wireless technologies, recycled materials, and emerging quantum materials, wearable sensors have undergone significant evolution through enhanced manufacturing processes such as 3D printing (Park et al., 2025). This dual application of sensors—for human health monitoring and structural safety—highlights their growing importance in fostering smarter, safer, and more sustainable ecosystems. The integration of cutting-edge technologies such as artificial intelligence (AI) and the Internet of Things (IoT) further amplifies their potential, enabling data-driven insights and more effective decision-making (Zainuddin et al., 2024).

This study explores the transformative potential of wearable sensors in sports sciences and structural monitoring, emphasizing their use in optimizing athlete health and maintaining infrastructure safety. It also examines the infrastructure and equipment necessary to establish a state-of-the-art wearable sensor research laboratory in a university setting. Such a facility would serve as a hub for interdisciplinary collaboration, advancing research and innovation in sensor technology. By bridging the gap between human health and structural integrity, wearable sensors represent a powerful tool for improving well-being, enhancing athletic performance, and ensuring the safety and sustainability of the environments where excellence unfolds. Their ability to simultaneously address human and structural challenges marks them as essential technologies in the pursuit of progress and resilience.

In line with this dual applicability, the emergence of hybrid sensor platforms—capable of monitoring both human physiological parameters and structural or environmental conditions—represents a new interdisciplinary research direction. These platforms combine sensing modalities from biomedical and structural domains, allowing for simultaneous data collection and interpretation across both human and engineered systems. This conceptual framework not only enhances technical integration but also sets the stage for novel applications in smart sports environments, disaster-resilient infrastructure, and cyber-physical-human systems.

WEARABLE SENSOR TECHNOLOGY IN SPORTS

Athletes require continuous monitoring of their physiological data to optimize performance, minimize the risk of injury, and maintain long-term health. Wearable sensors have emerged as indispensable tools in this regard, enabling real-time measurement of parameters such as heart rate, muscle activity, body temperature, and movement (Xue et al., 2024). These sensors facilitate the development of personalized training programs by tracking metabolic processes during endurance training, identifying muscle fatigue, and providing critical data to prevent potential injuries. By leveraging advanced sensor systems and automated analytics, wearable technology offers a proactive approach to injury prevention, monitoring soft-tissue stress, and reducing heat-related risks (Kenjayeva et al., 2024; Kovoor et al., 2024).

Beyond performance optimization, wearable sensor technology also plays a crucial role in health monitoring and early diagnosis of potential health issues. For instance, it supports the identification of long-term risks such as neurodegenerative diseases and obesity by tracking motor skills and cognitive abilities over time. Subtle changes in motor movements can serve as early indicators of conditions like dementia, while risk factors associated with obesity can be detected by monitoring daily activities and metabolic indicators. Flexible and wearable electrochemical sensors, which continuously observe physiological changes through biomarkers, further enhance these capabilities, allowing for tailored interventions and recovery programs (Liu et al., 2024).

Moreover, wearable sensors provide precise data on movement patterns, biomechanics, and physiological responses, enabling athletes to receive immediate feedback. This objective assessment helps minimize subjective biases, supporting data-driven decision-making for training adjustments and performance enhancement (Prabha et al., 2024). Advanced methodologies, such as continuous feature-extraction techniques like Functional Principal Component Analysis, have proven effective in modelling athletic performance, demonstrating the importance of sophisticated data processing approaches (White et al., 2024).

The integration of artificial intelligence and Internet of Things (IoT) technologies has further expanded the utility of wearable sensors. These advancements make it possible to monitor both individual athletes and structural health, such as the safety and durability of sports facilities. In earthquake-prone regions, for example, structural health monitoring (SHM) sensors integrated with wearable technologies can detect vibrations and damage, ensuring the safety of both facilities and athletes (Kolotovichev & Shakhramanyan, 2022; Sarmadi et al., 2023).

In conclusion, wearable sensor technology has transformed sports sciences by offering comprehensive solutions for performance enhancement, injury prevention, and health monitoring. From real-time physiological tracking to early diagnosis of health risks and ensuring structural safety, these technologies demonstrate their immense potential in advancing both individual and collective well-being in sports.

STRUCTURAL HEALTH MONITORING SENSORS AND APPLICATIONS IN SPORTS FACILITIES

Structural Health Monitoring (SHM) sensors (Lie et al,2016), and wearable sensor technologies are becoming indispensable in modern sports addressing both athlete performance and facility safety (Liu et al, 2024). SHM systems are designed to monitor the structural integrity of venues (Avci et al, 2024), while wearable sensors focus on tracking athletes' physiological parameters. The integration of these technologies has revolutionized sports science by creating a comprehensive approach to monitoring and management, blending advanced tools such as smartphone sensors, flexible wearable devices, and cutting-edge infrastructure monitoring technologies.

Wearable sensor technology, while traditionally associated with tracking physiological data like ECG, EEG, and EMG, is increasingly being integrated with smart health monitoring systems (Rukundo, 2024). In data fusion context, these sensor data can be easily correleted with advanced SHM systems including environmental health monitoring systems data such as temperature and air quality (e.g. Carbon dioxide and PM2.5 levels) for sports facilities and large gymnasiums (Liu et al., 2024). This synergy not only enhances athlete health monitoring but also contributes to infrastructure safety. For example, in earthquake-prone regions, SHM sensors can detect vibrations and structural damage, ensuring the safety of facilities (Chandrakumar et al., 2022). These systems are vital for real-time damage assessment, providing data that supports predictive maintenance and disaster readiness.

Smartphone sensing technology has also emerged as a practical and cost-effective solution for SHM. Equipped with sensors such as accelerometers, gyroscopes, and GPS, smartphones are now used for vibration- and vision-based monitoring of sports venues. These devices enable facility managers to gather real-time data on structural movements and vibrations, offering an accessible alternative to traditional, expensive monitoring systems (Sarmadi et al., 2023).

Flexible wearable sensors, on the other hand, focus on athletes, offering real-time monitoring of critical health parameters. These portable, flexible devices allow natural movement during training or competition while delivering insights into vital signals. Leveraging IoT technologies, they provide comprehensive health management solutions that help optimize performance and prevent injuries (Sun et al., 2022). Their dual capability to monitor individual athletes and integrate with SHM systems highlights their transformative potential.

On the other hand, advanced SHM sensor technologies such as fiber optics, laser vibrometry, and MEMS are pivotal for non-destructive testing and monitoring of sports facilities (Hassani & Dackermann, 2023). These sensors offer unparalleled accuracy and reliability in detecting structural changes, making them essential for ensuring long-term safety and functionality. By identifying potential issues early, these systems help reduce maintenance costs and prevent catastrophic failures (Hassani & Dackermann, 2023). A notable example of SHM in action is the Ekaterinburg Arena, which employs a sophisticated system comprising tiltmeters and strain gauges to continuously monitor its structural integrity. This system provides actionable data for predictive maintenance, ensuring the safety of athletes, spectators, and the facility itself (Kolotovichev & Shakhramanyan, 2022).

By combining wearable sensor technology with SHM systems, sports environments can be managed more effectively, ensuring the well-being of athletes and the safety of sports infrastructure. These advancements underscore the transformative power of SHM and wearable sensors in creating safer, more sustainable, and high-performing sports ecosystems.

LABORATORY REQUIREMENTS FOR WEARABLE SENSORS

A laboratory designed for wearable sensor research at a university must adopt a multidisciplinary approach. The design, production, calibration, and testing of sensors necessitate an infrastructure that spans multiple scientific disciplines, ensuring a robust platform for innovation in wearable technology. Such a facility must integrate advanced technologies and resources to comprehensively address the intricate needs of wearable sensor development. Key components include 3D printing systems and extrusion machines, essential for fabricating sensors with a range of biocompatible materials that are crucial for functionality and durability. The selection of materials, from flexible polymers to advanced conductive composites, is vital as they significantly influence the sensors’ performance and user comfort. Additionally, the lab requires sophisticated electrophysiology and biomechanics testing equipment to ensure that the sensors operate in harmony with human physiology. Environmental testing equipment is also necessary to validate the sensors’ durability under varied climatic conditions. Wireless communication testing and calibration systems are indispensable for maintaining the accuracy and reliability of data transmission. Furthermore, advanced data analysis and simulation software, which utilizes machine learning algorithms, is crucial for processing complex datasets and refining sensor designs. By harmonizing these components, the laboratory not only advances the field of wearable sensors but also enhances their practical application, enriching both the academic environment and broader societal uses. Figure 1 presents an example of future laboratory devices used for wearable sensor prototype development.

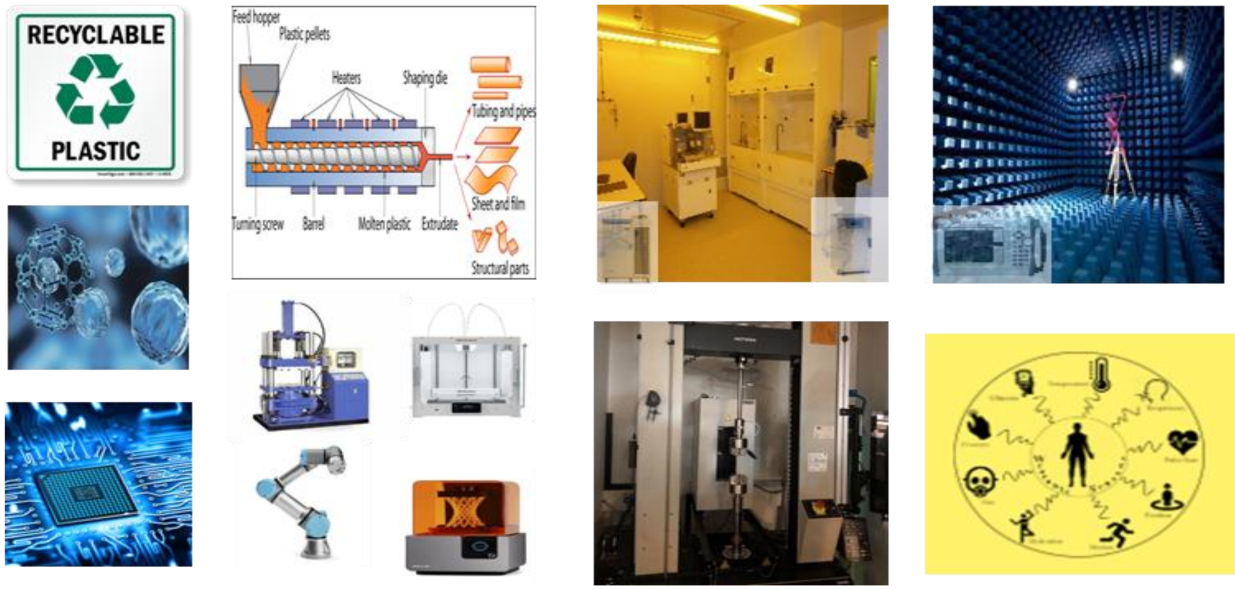

Figure 1. Example of future test and prototyping laboratory potential devices and environment for wearable sensors

3D printing systems and extrusion machines

Extrusion-based 3D printing methods, such as Fused Deposition Modeling (FDM), are widely regarded as the most practical choice for producing wearable sensors (Moreno-Rueda et al., 2024; Gupta et al., 2023). Their compatibility with a diverse range of biocompatible and functional materials, combined with their cost-effectiveness and accessibility, makes them indispensable in this field. Unlike alternative methods such as Stereolithography (SLA) or Selective Laser Sintering (SLS), which often require specialized or rigid materials (Miller et al., 2023), extrusion-based techniques are uniquely suited to handle flexible polymers like PLA, TPU, and PDMS—materials that are critical for wearable applications (Altıparmak et al., 2022; Li et al., 2023). Furthermore, extrusion-based systems are not only more affordable but also generate minimal material waste compared to powder-based methods, which adds to their appeal for research and small-scale production (Altıparmak et al., 2022; Haghighi, 2023). The ability of these printers to facilitate rapid prototyping and iterative design refinements enables the creation of highly customized sensor components tailored to specific needs. Their simplicity of operation and widespread availability in university laboratories and research facilities further underscore their significance. Additionally, extrusion devices are pivotal not only for producing composite filament and creating 3D-printed sensors but also for encapsulating electronic sensors (Pekgor et al., 2021). Collectively, these advantages position extrusion-based 3D printing as a cornerstone technology in the advancement of wearable sensor development.

Materials for wearable sensors

The choice of materials for wearable sensors is pivotal, influencing their functionality, durability, and adaptability across varied applications in sports sciences, healthcare, and beyond (Fu, 2024). Wearable sensors necessitate materials that are not only mechanically robust and biocompatible but also capable of conducting electrical signals, resisting environmental stress, and integrating seamlessly with human skin or other substrates (Rodrigues et al., 2020).

Biocompatible polymers like polydimethylsiloxane (PDMS), thermoplastic polyurethane (TPU), and polylactic acid (PLA) are essential due to their flexibility, lightweight nature, and skin compatibility. PDMS is particularly valued for its elasticity and thermal stability, making it ideal for sweat monitoring patches. These patches are often produced using extrusion-based 3D printing techniques, which enable the creation of flexible and precise components (Norton et al., 2023). TPU offers excellent durability and stretchability, suitable for flexible electronics, and is often processed through Fused Deposition Modeling (FDM), allowing for customized designs and iterative prototyping (Marco et al., 2024). PLA, known for its biodegradability, is increasingly used in 3D-printed sensor components, emphasizing sustainability. This polymer is compatible with FDM and is prized for its ease of processing and eco-friendly properties (Naveed & Anwar, 2024).

Conductive polymers, such as PEDOT:PSS, polyaniline, and polypyrrole, are critical for the detection and transmission of electrical signals. These polymers find applications in flexible circuits and real-time monitoring biosensors. They are often printed using Direct Ink Writing (DIW) or other extrusion-based methods, allowing for precise deposition of conductive inks, which ensures uniformity and functionality in sensor components (Hou et al., 2024).

Nanomaterials like graphene, carbon nanotubes (CNTs), and MXenes offer exceptional electrical, mechanical, and optical properties, making them indispensable for advanced wearable sensors used in applications such as strain sensors, bioelectronic devices, and energy storage systems. These materials are typically integrated into sensor designs through additive manufacturing techniques like Aerosol Jet Printing or DIW, enabling precise deposition of nanomaterial-based inks onto flexible substrates (Banik et al., 2024; Yang et al., 2024).

Metallic inks, including silver and gold nanoparticles as well as copper-based conductive inks, are crucial in the realm of printed electronics and low-power wearable devices due to their high conductivity and ease of deposition. These materials are commonly applied through inkjet printing or screen-printing methods, which facilitate high-resolution patterning on flexible substrates, ideal for applications like RFID tags and other wearable components (Yu et al., 2024).

Elastomers and hydrogels are vital for applications that require stretchable and skin-adherent sensors. Silicone elastomers, for instance, provide durability essential for monitoring joint movement, while hydrogels offer biocompatibility and moisture retention, critical for biosensors. Elastomers like silicone are often processed using extrusion-based 3D printing techniques (Yan Li et al., 2024), whereas hydrogels are typically fabricated through specialized 3D bioprinting methods that ensure precise control over material placement and structure (Shen et al., 2024).

Emerging materials like self-healing polymers (Vo Thi, 2024), quantum materials (Hammed et al., 2024), and recyclable bio-based materials (Ritesh Kumar et al., 2024) are pushing the boundaries of wearable sensor technology by addressing durability and sustainability concerns. These advanced materials are being explored through cutting-edge 3D printing methods such as multi-material extrusion and hybrid additive manufacturing, enabling the integration of multiple functionalities into a single sensor design.

Moreover, material functionalization techniques, including nanocomposites that combine polymers with nanomaterials and surface treatments such as plasma etching, enhance sensor performance by improving conductivity, mechanical strength, and adhesion (de Barros et al., 2023). These innovations collectively advance the field, ensuring that wearable sensors are efficient, adaptable, and environmentally conscious, while leveraging appropriate 3D printing methods for each material to maximize their potential in sensor applications.

ELECTROPHYSIOLOGY, BIOMECHANICS, MECHANICAL TESTING AND MATERIAL CHARACTERIZATION EQUIPMENT

In the domain of wearable sensor technologies, a comprehensive suite of testing methodologies is indispensable for advancing their development and ensuring their efficacy (Ravizza et al., 2019). Critical to this process are electrophysiology, biomechanics, mechanical testing, and material characterization equipment, each serving a unique role in the validation of these innovative devices. Electrophysiological tools such as electromyography (EMG) and electrocardiography (ECG) are foundational in ensuring that the sensors are not only biocompatible but also proficient in accurately recording vital biological signals, including muscle activity and cardiac rhythms. Such capabilities are crucial for sensors designed to interface directly with human physiology (Singh et al., 2024). Complementing this, biomechanical testing systems are employed to evaluate the functional performance of sensors by analyzing movement data. These systems allow researchers to simulate real-world conditions to ascertain how the sensors perform during actual use, providing invaluable data on their operational reliability (Vassiouk et al., 2020). Mechanical testing further scrutinizes the robustness and endurance of wearable sensors. Through a battery of stress tests—such as tensile, compression, and bending tests, along with evaluations under varying conditions of temperature, humidity, and mechanical stress—this testing ensures that the sensors can withstand the physical demands of daily wear and diverse environmental exposures (Persons et al., 2021). Material characterization is equally critical, offering a microscopic view of the materials used in sensor fabrication. Techniques such as scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) delve into the microstructural details and chemical properties of these materials (Akhtar et al., 2018). Additional analyses, like X-ray diffraction (XRD) and thermal evaluations through thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), provide insights into the crystalline structures and thermal stability, respectively. Dynamic mechanical analysis (DMA) further investigates the materials' elastic and damping properties across temperature ranges (Menard et al., 2015). Collectively, these sophisticated analytical techniques ensure that the materials and technologies employed in wearable sensors meet rigorous standards for biocompatibility, durability, and functionality (De Lima et al., 2023). By integrating these diverse methodologies, the field of wearable sensors is propelled forward, enhancing their application in health monitoring and sports science, and ensuring that these devices can reliably perform in human-centered applications.

Environmental testing equipment

Testing the durability of wearable sensors under varying environmental conditions is a critical function of the laboratory. Climatic chambers evaluate performance under extreme temperatures, cold, and humidity, while pressure test chambers measure resistance to pressure changes. These tests enhance the usability of sensors in diverse environments (Papapostolou et al., 2017).

Wireless communication testing devices and calibration systems

Like other wireless systems, evaluating the performance of wearable sensors requires specialized equipment, including RF non-echoing chambers, vector network analyzers (VNA), and spectrum analyzers (Kango et al., 2024). For sensors that enable wireless data transmission, such as those using RFID, Bluetooth, or NFC protocols, wireless communication testing devices measure data transmission speed, range, and connection stability (Čolaković et al., 2021). Calibration systems are also essential for ensuring sensor accuracy, and regular calibration is necessary to maintain reliability (Poddar et al., 2017).

Data analysis and simulation software

Advanced data analysis software is essential for processing the large datasets generated by sensors. Accurate interpretation of sensor data can be significantly enhanced using machine learning algorithms. In modern laboratories, real-time data processing and simulation tools are also integral components (Bojja et al., 2024). According to the literature, such software is widely accepted when it enables meaningful insights from large-scale or high-frequency sensor data, particularly in systems that demand rapid decision-making and real-time feedback (Dinkar et al., 2024). Its value increases when paired with machine learning for pattern recognition or anomaly detection, and when integrated with simulation platforms such as digital twins or smart systems. These tools are considered critical in fields like structural health monitoring, smart manufacturing, and wearable health technologies, where timely and data-driven decisions are vital.

Finally, a state-of-the-art laboratory for wearable sensor research requires a multidisciplinary infrastructure that seamlessly integrates advanced fabrication, testing, and analytical capabilities. The development of wearable sensors demands precision in every stage, from material selection to real-world validation. By incorporating 3D printing systems and extrusion machines, the laboratory enables the rapid prototyping and fabrication of customized sensor designs using biocompatible and functional materials (Sekeroglu, et al., 2025). Sophisticated electrophysiology and biomechanics equipment ensure that sensors are both physiologically compatible and capable of accurately capturing critical biological signals, such as muscle activity, heart rhythms, and movement patterns (Flynn et al., 2023). Meanwhile, mechanical and material characterization systems evaluate the robustness, flexibility, and thermal properties of sensor materials, ensuring they can withstand diverse environmental and operational conditions.

As illustrated in Figure 2, this lab-scale workflow demonstrates our approach to sustainable sensor production. The process begins with the transformation of recycled materials into functional filaments, emphasizing eco-conscious design. These filaments are then employed in 3D printing to fabricate flexible and high-precision sensor prototypes. Subsequently, the prototypes are integrated into hardware-software systems capable of real-time data acquisition, processing, and wireless communication. This integrated development pipeline synthesizes material science, digital manufacturing, and embedded systems to produce wearable sensors tailored for applications in health monitoring, sports science, and human performance assessment.

Furthermore, environmental testing systems validate sensor durability under varied climatic and operational conditions, while wireless communication and calibration tools ensure accuracy, reliability, and seamless data transmission across platforms. Advanced data analysis and simulation software, powered by machine learning algorithms, allows researchers to interpret complex datasets, refine sensor designs, and optimize system performance.

By harmonizing these interconnected components, the laboratory provides a dynamic platform for the development of next-generation wearable sensors. This holistic approach not only fosters innovation in health and sports sciences but also prepares researchers to address emerging challenges in wearable technology. Ultimately, such a facility serves as a bridge between academic research and real-world applications, driving advancements that improve human health, performance, and sustainability.

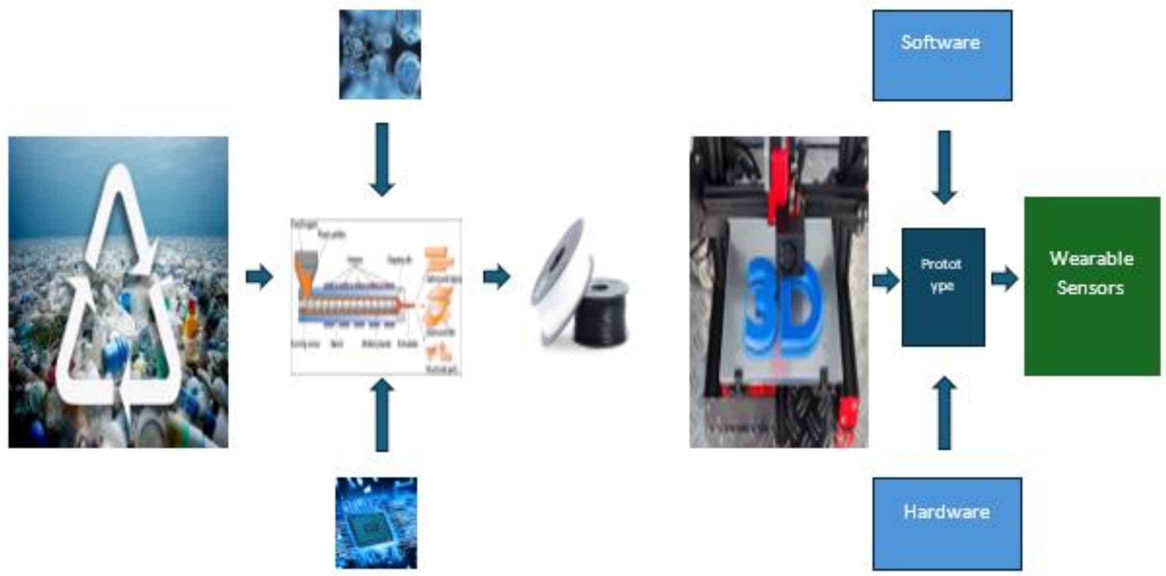

Figure 2. Sample of Sustainable (wearable)sensor production in Lab Conditions

Future perspectives

The evolving landscape of wearable sensors is expected to play a pivotal role in athlete health and sports psychology by enabling a range of forward-looking applications. One emerging direction involves assessing mental states through physiological signal monitoring. By capturing indicators such as heart rate variability, skin conductivity, or muscle activity, it becomes possible to interpret mental readiness and stress levels. Strategically positioned sensors, paired with intelligent algorithms, may offer non-invasive, data-driven evaluations of psychological resilience (Taskasaplidis et al., 2024).

Another promising avenue is the integration of mcroelectromechanical systems (MEMS) to facilitate skin and microflora analysis. These wearable platforms could detect subtle shifts in the skin's biochemical environment—such as variations in pH or microbial activity—potentially allowing for early insights into immune health and recovery needs (Rodrigues et al., 2020).

Additionally, advances in micro-movement tracking are anticipated to enhance the precision of physical performance assessments. By analyzing subtle vibrations and fine motor actions, these systems may support detailed evaluations of muscle coordination and postural control, offering new tools for injury prevention and performance optimization in activities demanding high stability, such as balance training and yoga (Gomez, & Giang, 2024).

Emotional state and rhythm regulation presents a compelling future direction for wearable sensor applications. By integrating biosensors with rhythm-based systems, physiological signals—such as heart rate and respiratory rhythm—can be transformed into personalized auditory feedback (Goverdovsky et al., 2016). This integration holds potential for stress reduction and motivation enhancement, particularly in scenarios involving pre-competition preparation or performance under pressure.

The evolution of wearable sensors is also expected to support real-time biofeedback through bidirectional communication interfaces. By continuously tracking indicators such as skin temperature or muscle activation, these systems can provide immediate visual or auditory cues to guide athletes toward optimal biomechanical form, thereby enhancing training efficiency and reducing error accumulation (Tedesco et al., 2021).

Another frontier involves dynamic sensor systems capable of altering their visual or tactile properties in response to physiological or psychological stimuli. Such adaptive feedback—e.g., color changes triggered by stress levels—could provide both athletes and coaches with intuitive, real-time insights during high-performance activities (Sekeroglu et al., 2025).

Advanced sensor platforms may also enable predictive modelling and rhythm optimization through AI-driven analysis. By synthesizing physiological data, movement patterns, and contextual factors, these systems could forecast performance trends, adapt training protocols dynamically, and mitigate injury risks with precision (Aditi et al., 2024).

Beyond individual monitoring, wearable systems could be leveraged to assess physiological responses to environmental stressors such as heat, humidity, or air quality. Emerging technologies may also support energy-autonomous operation by harvesting power from kinetic or thermal sources, further promoting sustainable deployment in long-duration settings (Naidu & Dhote, 2025).

In team-based contexts, sensor networks have the potential to transform collective performance analysis. By capturing spatiotemporal dynamics of individual players, these systems can evaluate synchronization, role-based interactions, and tactical cohesion—offering coaches a data-informed basis for strategic refinement (Gudmundsson & Horton, 2017).

Lastly, wearable sensors may play a critical role in pain perception analysis and early injury detection. Through monitoring micro-variations in muscle tension or dermal temperature, such systems could identify signs of discomfort or strain, allowing for early interventions and expedited recovery processes (Moscato et al., 2023).

When combined with data fusion and machine learning, wearable sensors offer even greater possibilities. The integration of data from various sensor technologies, including accelerometers, electromyography (EMG), and sweat analysis—facilitates a comprehensive assessment of athletes' physical and mental states (Sekeroglu et al., 2025). This holistic approach is transformative in sports sciences, as it enables the aggregation of multifaceted data streams into a unified analysis platform. Through the application of advanced machine learning algorithms, these integrated data sets can be meticulously analyzed to predict potential health issues, which could preemptively be addressed through personalized training adjustments. Furthermore, this integration supports the optimization of athletic performance by tailoring interventions that are specifically aligned with the unique physiological and psychological profiles of each athlete. This strategy not only enhances individual performance but also contributes to the broader objectives of sports science by promoting health, safety, and peak performance through data-driven insights.

The utility of wearable sensor technologies extends beyond their application to athletes, providing pivotal benefits for trainers and referees through precise monitoring capabilities (De Fazio et al., 2023). These sensors can track physical exertion, stress levels, and hydration metrics with high accuracy, offering a valuable tool for managing athletes' performance and well-being. The integration of such technologies into the wider sports ecosystem facilitates a multifaceted enhancement of performance, ensuring safety, and promoting the overall health of all individuals involved.

Furthermore, the real-time data generated by wearable sensors provides actionable insights that support the integrity and fairness of sports competitions (Da Silva, 2024). This technology aids in making informed decisions that align with sustainable practices, ultimately contributing to a more equitable sporting environment. By enabling a thorough understanding and response to the physiological demands faced by athletes, wearable sensors not only optimize individual performance but also enhance the collective experience, promoting a more inclusive and technologically sophisticated sports culture. In addition, the future of wearable sensors extends beyond personal health monitoring and performance optimization, finding a vital role in Structural Health Monitoring (SHM) for sports facilities. Wearable sensors integrated with SHM systems create a comprehensive ecosystem where the well-being of athletes and the safety of the environment coexist harmoniously. These sensors, equipped with advanced detection capabilities, can assess vibrations, structural stress, and environmental conditions in real-time. For instance, flexible strain sensors worn by athletes or embedded in equipment could simultaneously monitor biomechanical performance and relay data on the structural stability of training platforms, stadiums, or gymnasiums (Zhu et al., 2021).

In regions prone to earthquakes or extreme weather, wearable sensors combined with SHM systems could enhance safety by detecting early signs of structural degradation. For example, wearable devices equipped with accelerometers and gyroscopes could work alongside embedded facility sensors to monitor both human movements and structural responses during high-impact events. This integration ensures not only the athletes' optimal performance but also the immediate identification of potential risks in their surroundings (Gobinath et al., 2024).

Additionally, wearable sensors could act as mobile extensions of fixed SHM systems. For instance, trainers or staff equipped with wearables might collect localized data as they move through a facility, identifying stress points or environmental inconsistencies. These sensors could provide early warnings to prevent catastrophic failures, ensuring the safety of thousands of athletes and spectators.

The dual functionality of wearable sensors in monitoring both human performance and structural integrity emphasizes their transformative potential. By creating a synergistic network between wearable devices and SHM systems, this technology fosters a safer, more resilient, and high-performing sports ecosystem, ensuring that athletes and their environments are equipped for peak performance and longevity.

Furthermore, wearable technologies, particularly RFID-based sensors, are transforming data collection and monitoring across various fields, including sports sciences (Pekgor et al., 2025). Their ability to operate wirelessly, without the need for direct physical connections, provides significant advantages such as seamless real-time data transmission, simplified deployment, and enhanced mobility. RFID-based sensors, in particular, stand out for their exceptional versatility due to their passive nature, which allows them to function without an onboard power source. This characteristic makes them lightweight, cost-effective, and well-suited for continuous monitoring in dynamic environments.

In sports applications, RFID sensors enable non-invasive tracking of athletes' physiological and biomechanical parameters, including heart rate, hydration levels, and movement patterns, without interfering with performance (Riente et al., 2023).

Their long-range communication capabilities and resilience in challenging environments, such as high-impact or moisture-rich conditions, further broaden their applicability. Moreover, RFID-based systems are ideal for large-scale monitoring, making them particularly useful in team sports or events involving multiple participants (Ianni et al., 2015).

Beyond athlete monitoring, RFID-based sensors also have significant applications in health and structural health monitoring (Pekgor et al., 2021). They enable real-time, non-invasive tracking of vital physiological parameters while also providing accurate data on structural stress, vibrations, and integrity, ensuring safety and reliability in dynamic environments such as sports facilities. The integration of these sensors with IoT platforms facilitates advanced data analytics, delivering actionable insights to optimize performance, prevent injuries, and enhance safety. As a cornerstone of modern wearable technologies, RFID-based sensors continue to drive innovation, bridging the gap between precision monitoring and user convenience.

DISCUSSION AND CONCLUSION

The conceptualization and development of hybrid sensor platforms that simultaneously monitor physiological dynamics in the human body and mechanical or environmental stressors in engineered structures represent a novel interdisciplinary frontier. While traditional sensor systems have evolved in separate silos—wearable health sensors within biomedical engineering and structural health monitoring (SHM) sensors within civil or mechanical engineering—recent advances in material science, flexible electronics, edge computing, and wireless communication infrastructures such as 5G and satellite-based systems are converging these fields into unified technological frameworks. These next-generation multimodal sensors are not limited to strain measurement but include integrated capabilities such as pressure mapping, temperature tracking, electrochemical sensing, acoustic emission detection, and motion analysis. Designed using flexible substrates, printable nanomaterials, and biocompatible composites, such sensors can be embedded both on the human body and within critical infrastructure. This enables real-time, dual-domain data acquisition that not only supports personalized health diagnostics but also ensures structural safety and resilience. Moreover, these hybrid systems can be interconnected through advanced networks—5G/6G, low-Earth orbit satellite telemetry, or IoT platforms—allowing data fusion between wearable devices and built environment sensors. For example, wearable pressure sensors used in athletic footwear can be co-developed with load sensors embedded in stadium flooring, enabling synchronized monitoring of biomechanical and structural stress. Similarly, sweat-analyzing electrochemical patches may detect corrosion markers when adapted for use in reinforced concrete. Although sensing modalities such as strain or biochemical markers have been deployed individually in their respective domains, their integrated co-design and deployment across a shared physical–digital infrastructure remains underexplored. Furthermore, the application of AI-based signal interpretation—capable of extracting cross-domain patterns and predictive insights—marks a transformative advancement. These developments define a new frontier for cyber-physical-human systems in smart sports environments, offering novel opportunities to enhance health, safety, and performance in synchrony.

Building upon this conceptual framework, our research demonstrates that the integration of wearable sensor technologies across health monitoring, athletic performance, and structural safety domains presents a significant opportunity for advancing both human-centered and infrastructure-focused applications. As evidenced throughout this study, wearable sensors offer robust capabilities for real-time tracking of physiological parameters, injury prevention, and performance optimization in athletic environments. Simultaneously, their deployment in structural health monitoring (SHM) frameworks enables early detection of physical stress, material fatigue, and environmental hazards in large-scale sports facilities.

The findings indicate that the establishment of multidisciplinary laboratories equipped with advanced fabrication and testing systems is essential to the effective development of these technologies. Additive manufacturing platforms—particularly extrusion-based 3D printing—enable the rapid prototyping of flexible and biocompatible sensor components (Ali et al., 2021), while material characterization techniques such as SEM, XRD, and FTIR ensure the precision, durability, and reliability of sensor materials (Fatimah et al., 2023). Furthermore, integration with wireless communication systems and machine learning-enabled analytics contributes to the transformation of raw sensor outputs into actionable insights, facilitating more informed decision-making in both training and structural management contexts.

From a sustainability perspective, the study highlights the growing significance of incorporating recycled and next-generation materials such as self-healing polymers (Wang & Urban, 2020), and quantum-enabled substrates into sensor design. These innovations not only extend sensor functionality but also align with broader goals in sustainable manufacturing and environmental resilience. Moreover, the potential for seamless data transmission via RFID, Bluetooth, or NFC-based systems enhances both mobility and system scalability, particularly in dynamic and high-demand settings such as competitive sports arenas.

Future trajectories in wearable sensor development are expected to converge with advancements in AI, MEMS, and bio-integrated systems. The capability to monitor neurophysiological states, detect micro-movements, and provide adaptive feedback in real-time suggests a broader paradigm shift—from passive sensing to proactive, personalized, and predictive monitoring (Wang et al., 2023). This shift will be particularly impactful in high-performance sports contexts where marginal gains can have significant competitive implications.

In conclusion, wearable sensor technology represents a pivotal convergence of biomedical engineering, materials science, and data analytics. The establishment of research laboratories that integrate these disciplines can catalyze innovations that serve both individual health and collective safety. By fostering a systems-level approach that spans human physiology and structural integrity, wearable sensor platforms offer transformative potential for academia, industry, and public health alike. Continued investment in interdisciplinary collaboration, sustainable materials, and intelligent analytics will be critical to realizing the full spectrum of benefits that wearable sensor technologies promise.

Recommendations

Based on their findings, Pekgor and colleagues outline several considerations that may contribute to the advancement of wearable sensor technologies in sports sciences and structural health monitoring. They emphasize the potential benefits of strengthening interdisciplinary collaboration among sports scientists, engineers, and materials researchers to support innovation. Investment in advanced manufacturing methods, such as 3D printing, is suggested as a way to improve sensor design and adaptability. The integration of recycled and quantum materials is highlighted as a promising direction to enhance performance while addressing sustainability concerns. Real-world testing is considered essential for validating sensor effectiveness in both athletic and infrastructural applications. The authors also note the importance of robust data security protocols to protect sensitive physiological and structural information. Furthermore, they point to the need for standardized data collection and analysis frameworks to support consistency across research settings. Lastly, strategies to reduce production costs are recommended to facilitate wider accessibility and practical deployment across sports and engineering domains.

Limitations and strengths

Wearable sensor technology demonstrates a range of notable strengths that enhance its applicability across both human health monitoring and structural integrity assessment. Its capacity for real-time data acquisition enables immediate physiological feedback for athletes and timely detection of potential infrastructural anomalies. The non-invasive nature of these devices facilitates continuous and user-friendly monitoring without disrupting physical performance or comfort. Furthermore, the integration of advanced materials—such as quantum-enabled substrates (Cantarella et al., 2023) and recycled polymers (Zheng et al., 2024)—supports enhanced device functionality while aligning with sustainability objectives. The scalability and adaptability of wearable sensors further allow for deployment across diverse domains (Domb, 2019), including competitive sports, clinical settings, and civil infrastructure.

Despite these advantages, certain limitations remain. First, the high cost of fabrication—particularly when involving emerging materials and precision manufacturing methods—poses a barrier to widespread adoption, especially in resource-limited environments (Ali et al., 2024), (De Sario Velasquez et al., 2024). Second, the accuracy and reliability of sensor data can be influenced by external variables, including temperature fluctuations, humidity, and inconsistent sensor placement on the body or structure (Wei et al., 2018). Third, the limited battery life and power consumption of wireless sensors represent ongoing technical challenges, particularly for applications requiring uninterrupted operation over extended periods (Yadav & Kumar, 2023). Additionally, the wireless transmission of sensitive health or structural data raises significant privacy and cybersecurity concerns, necessitating the development of robust data protection frameworks (Charumathi et al., 2024). Lastly, current evidence remains constrained by a lack of longitudinal studies assessing the long-term durability, biocompatibility, and performance of wearable sensors under real-world conditions (Lu et al., 2023).

Addressing these limitations while capitalizing on the established strengths of wearable sensor systems will be essential for advancing their implementation in both sports science and structural health monitoring. Continued interdisciplinary research, cost optimization, and development of standardized protocols are critical for enhancing their reliability, accessibility, and broader societal impact.

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Destek ve Teşekkür Beyanı/ *Statement of Support and Acknowledgment*

Bu çalışmanın yazım sürecinde katkı ve/veya destek alınmamıştır.

No contribution and/or support was received during the writing process of this study.

Çatışma Beyanı/ *Statement of Conflict*

Araştırmacıların araştırma ile ilgili diğer kişi ve kurumlarla herhangi bir kişisel ve finansal çıkar çatışması yoktur.

Researchers do not have any personal or financial conflicts of interest with other people and institutions related to the research.

Etik Kurul Beyanı/ *Statement of Ethics Committee*

Bu çalışmada kullanılan veriler, kamuya açık ve etik kurallara uygun olarak erişilebilen kaynaklardan elde edilmiştir. Etik kurul izni gerektirmeyen bir çalışmadır.

The data used in this study were obtained from publicly available and ethically accessible sources. It is a study that does not require ethics committee permission.