ARTICLE

Foresight Study on Biosensor Technologies: dual-use applications in civilian and military domains

Estudo de Prospectiva sobre Tecnologias de Biossensores: aplicações de uso dual nos âmbitos civil e militar

ABSTRACT

This foresight study examines the advancement of biosensor technologies with dual-use potential in both civilian and military contexts. The objective is to anticipate technological trends, assess levels of technological maturity, and identify relevant applications aimed at health monitoring, physical performance enhancement, and operational readiness. Biosensors have undergone significant evolution, transitioning from rudimentary physiological detectors to sophisticated wearable, implantable, and ingestible systems capable of real-time physiological monitoring. Key advancements include device miniaturization, the integration of artificial intelligence, and the adoption of wireless communication protocols, which collectively expand their applicability in demanding operational environments. In military settings, these technologies enable continuous monitoring of critical indicators such as fatigue, stress, and injury risk. In civilian domains, biosensors are reshaping practices in personalized medicine, occupational health, sports science, and telehealth. The methodological framework incorporates horizon scanning, trend analysis of patents and scientific publications, assessment of Technology Readiness Levels (TRLs), and strategic tools such as SWOT and PESTEL analyses. The findings indicate that the United States leads the field in terms of patent filings and scholarly output, with particular emphasis on neurophysiological sensors and multimodal platforms. Future scenarios projected for the 2030–2040 horizon range from fully integrated ethical adoption across sectors to challenges related to data privacy, cyber-biological threats, and dual-use governance. Responsible advancement of these technologies requires coordinated investments in research and development, interdisciplinary collaboration, and the establishment of robust ethical and regulatory frameworks. The study concludes by underscoring the strategic importance of biosensors in enabling resilient, data-driven health and defense systems.

Keywords: Physiological monitoring. Wearable Electronic Devices. Human Performance.

RESUMO

Este estudo prospectivo analisa o desenvolvimento de tecnologias de biossensores com potencial de uso dual nos âmbitos civil e militar. Busca-se antecipar tendências, avaliar níveis de maturidade tecnológica e mapear aplicações voltadas ao monitoramento da saúde, ao aprimoramento do desempenho físico e à prontidão operacional. Os biossensores evoluíram significativamente, passando de dispositivos rudimentares para sistemas vestíveis, implantáveis e ingeríveis, com capacidade de monitoramento fisiológico em tempo real. Avanços como a miniaturização, a incorporação de inteligência artificial e o uso de comunicações sem fio ampliam sua aplicabilidade em ambientes operacionais exigentes. No contexto militar, essas tecnologias permitem o monitoramento contínuo de indicadores como fadiga, estresse e risco de lesão. Já na esfera civil, transformam práticas em medicina personalizada, saúde ocupacional, ciências do esporte e telessaúde. A metodologia emprega varredura de horizonte tecnológico (horizon scanning), análise de tendências em patentes e publicações, avaliação do Nível de Maturidade Tecnológica (Technology Readiness Level – TRL) e as ferramentas SWOT e PESTEL. Os resultados indicam a liderança dos Estados Unidos no desenvolvimento da área, com destaque para sensores neurofisiológicos e plataformas multimodais. Projeções para 2030–2040 incluem cenários que vão desde integração ética plena até desafios relacionados à privacidade, riscos ciberbiológicos e governança do uso dual. A exploração responsável dessas tecnologias exige investimentos coordenados em pesquisa, cooperação interdisciplinar e marcos éticos e regulatórios robustos. Conclui-se que os biossensores constituem ativos estratégicos para a construção de sistemas de saúde e defesa mais resilientes e orientados por dados.

Palavras-chave: Monitoramento fisiológico. Dispositivos eletrônicos vestíveis. Desempenho humano.

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1 Introduction

Biosensors constitute a transformative class of analytical devices engineered to detect biological signals and convert them into quantifiable data. These systems typically comprise a bioreceptor, a transducer, and an electronic unit responsible for signal processing and data transmission. While initially developed for biomedical diagnostic applications, biosensors have undergone significant technological advancement and functional diversification, including health monitoring, physical performance, occupational safety, and, increasingly, military applications (Friedl *et al*., 2018).

In civilian contexts, biosensors are widely employed for monitoring vital signs, managing chronic diseases, supporting physical rehabilitation, and enhancing athletic performance (Friedl *et al*., 2018; Aidman, 2020). In military environments, their potential becomes even more pronounced. Biosensors provide continuous, real-time data on individuals' physiological and cognitive states, thereby supporting decision-making under high-risk conditions (Marson & Guimarães, 2021; Silva, 2022). These devices enable early detection of fatigue, dehydration, cognitive overload, and injury risk - factors that are critical for sustaining operational readiness and ensuring survival in complex mission scenarios.

Technology foresight plays a pivotal role in anticipating technological transformations and guiding strategic planning efforts. By analyzing emerging trends, levels of technological maturity, and potential dual-use trajectories, foresight studies provide critical support for informed decision-making across governmental, defense, health, and industrial sectors (Gibson *et al*., 2018; Alpysbayev & Alpysbayev, 2023). In the case of biosensors, the convergence of biotechnology, artificial intelligence, and digital communication systems has created not only unprecedented opportunities but also increasingly complex ethical, legal, and security challenges.

Understanding the dual-use nature of biosensors is particularly salient in today's shifting geopolitical landscape. Devices originally designed for civilian health monitoring can be rapidly adapted for military purposes, either to enhance warfighter effectiveness or, conversely, to serve as instruments of surveillance and control. This civil-military convergence underscores the need for proactive governance frameworks and strategic autonomy in the development and deployment of biosensing technologies (Friedl *et al*., 2018).

As these technologies become more advanced and embedded within both civilian and defense systems, the demand for coordinated strategic foresight and ethical oversight intensifies. In this context, the central aim of the present scientific inquiry is to provide a comprehensive and forward-looking analysis of biosensor technologies, with a particular emphasis on their dual-use potential, innovation trajectories, and implications for public policy. The study seeks to anticipate key trends and critically assess how such technologies may reshape human performance monitoring and inform decision-making processes across civil and defense domains, in both peacetime and conflict settings.

2 Methodological Approach

To map the technological trajectory and dual-use implications of biosensor technologies across civilian and military domains, this foresight study adopts a multimethod framework that integrates both qualitative and quantitative approaches. The employed methodology encompasses horizon scanning, assessment of technological maturity levels, trend analysis, and the application of strategic tools such as SWOT and PESTEL matrices. This integrative approach ensures a comprehensive and anticipatory perspective, attuned to both the dynamics of technological innovation and the operational demands of dual-use environments.

2.1 Horizon Scanning of Technological Developments

Systematic horizon scanning was conducted across scientific databases (such as PubMed and ScienceDirect), technology platforms (IEEE Xplore, SpringerLink), and patent repositories (LENS, WIPO). The search focused on keywords including "biosensor," "physiological monitoring," "wearable device," "military performance," and "dual-use technology." The analysis revealed a marked increase in both academic publications and patent filings since the early 2000s, with particular emphasis on neurophysiological and neuromechanical sensors, as well as multimodal systems that integrate physical and cognitive monitoring capabilities (Marson & Guimarães, 2021).

2.2 Technology Readiness Level (TRL) Assessment

To assess the maturity level of innovations in biosensor technologies, this study employed the Technology Readiness Level (TRL) model. Each technology was classified on a scale ranging from TRL 1 (basic principles observed) to TRL 9 (system proven in operational environments). Most biosensors currently applied in military monitoring fall within TRL levels 5 to 7, indicating that these technologies have been validated in controlled settings but have not yet been fully integrated into standard operational procedures.

2.3 SWOT and PESTEL Analyses

To evaluate the strategic viability of biosensor technologies, this study applied two complementary frameworks: SWOT (Strengths, Weaknesses, Opportunities, and Threats) and

PESTEL (Political, Economic, Social, Technological, Environmental, and Legal). The SWOT analysis underscored key strengths such as the role of biosensors in enabling personalized training and real-time health surveillance, while also identifying weaknesses related to data privacy concerns and energy limitations in wearable systems. The PESTEL analysis offered a broader perspective, addressing regulatory gaps, market trends, ethical risks, and the geopolitical implications of dual-use sensing technologies.

By triangulating multiple data sources and analytical tools, this methodological framework aims to deliver a comprehensive foresight analysis - one that not only identifies key trends but also anticipates challenges and strategic considerations pertinent to both civilian and military ecosystems.

3 Results and Discussion

3.1 Current State of Biosensor Technologies

Biosensor technologies have advanced rapidly over the past two decades, evolving from laboratory-confined instruments into compact, user-friendly devices capable of field deployment. These systems are increasingly integrated into wearable devices and connected platforms, enabling real-time physiological and environmental monitoring (Marson & Guimarães, 2021; Friedl, 2018). At present, biosensor applications span various sectors, including healthcare, sports science, occupational safety, and becoming increasingly prominent, military operations.

3.2 Types of Biosensors

A wide range of biosensor technologies is either currently operational or under active development (Marson *et al*., 2023; Friedl *et al*., 2018). Principal types are as follows:

- Electromyography (EMG): EMG sensors detect the electrical activity generated by skeletal muscles. They are widely applied in ergonomics and physical rehabilitation and are increasingly utilized in military settings to assess muscular fatigue and motor performance under physical load.

- Electroencephalography (EEG): EEG sensors measure electrical brain activity and are employed to evaluate cognitive workload, stress levels, and mental fatigue. Their potential application in supporting tactical decision-making and enhancing cognitive readiness has attracted growing interest within defense institutions.

- Electrocardiography (ECG): ECG biosensors monitor cardiac function and are essential for detecting stress responses, measuring exertion intensity, and providing early warnings of cardiovascular overload during high-demand physical activities.

- Inertial Measurement Units (IMU): These units incorporate accelerometers and gyroscopes to track movement and perform biomechanical analyses. IMUs are vital tools for gait analysis, load carriage studies, and assessing movement efficiency in both athletic and military populations.

- Biochemical and Optical Biosensors: These sensors detect biomarkers such as glucose, lactate, or hydration status through saliva, sweat, or interstitial fluid. They emerge as valuable tools for both chronic disease management and on-field diagnostics.

- Electrodermal Activity (EDA): Also known as galvanic skin response sensors, EDA devices monitor changes in skin conductance associated with stress. When combined with heart rate variability measurements, they provide critical insights into psychophysiological status under operational stress conditions.

3.3 Technological Maturity and Development

Most commercially available biosensors currently fall within Technology Readiness Levels (TRL) 6 to 8, indicating that they have been validated in relevant environments and are approaching full operational capability. However, biosensors specifically designed for military applications, featuring secure data transmission, extended battery life, and enhanced environmental durability, remain at TRL levels 4 to 6. This suggests that, while these systems have undergone experimental validation, their integration into field operations remains limited (Pohanka, 2019; Rausch *et al*., 2022).

Advanced wearable platforms such as BITalino, Hexoskin, and Zephyr BioHarness have been tested in military and research settings, offering multichannel signal acquisition capabilities (e.g., ECG, EMG, EEG, respiration, and temperature) along with real-time data transmission.

Nonetheless, several challenges persist, including signal noise interference, limited interoperability with military communication systems, and vulnerabilities in cybersecurity infrastructure.

3.4 Applications in the Civilian Sector

Biosensors have been widely adopted across a variety of civilian sectors, with particularly notable applications in healthcare, sports science, and occupational safety. In the healthcare domain, these technologies enable remote monitoring of chronic conditions such as cardiac arrhythmias and diabetes, thereby facilitating early diagnosis and improving the quality of care for elderly populations and individuals with limited mobility (Dalloul *et al*., 2023).

Within sports science, biosensors are employed to track training load, monitor the timing of muscle activation, prevent injuries, and provide objective feedback on physical performance (Cheng *et al*., 2024). In occupational safety contexts, biosensors contribute substantially to the early detection of fatigue, real-time postural analysis, and monitoring of exposure to hazardous environments, including those in mining, construction, and aviation (Malasinghe *et al*., 2019).

The growing adoption of biosensors in both clinical and non-clinical settings can be attributed to several factors: their affordability, ease of use by both professionals and end-users, and their ability to continuously and non-invasively generate large volumes of physiological data. These data streams, in turn, power predictive analytics systems capable of identifying physiological patterns associated with health risks, pathological conditions, or performance fluctuations.

Such capabilities support early interventions, enable personalized strategies, and promote the optimization of health outcomes and physical performance across a broad spectrum of applications.

3.5 Application in the Military Sector

In the defense context, biosensors are assuming an increasingly strategic role, particularly in efforts aimed at optimizing the physical and cognitive performance of military personnel (Marson & Guimarães, 2021). Among their principal applications are the monitoring of physiological overload, neuromuscular fatigue, and cardiovascular resilience during high-intensity training and field operations (Almer *et al*., 2022). By continuously collecting biometric data, these devices enable real-time tracking of physical readiness and tolerance to physical stress, thereby supporting injury prevention and facilitating personalized adjustments to operational demands.

Beyond physical performance, biosensors are also being employed to assess warfighters' cognitive readiness through the analysis of brain electrical activity and heart rate variability. These physiological markers offer valuable insights into alertness levels, situational awareness, and mental fatigue, factors that are critical for decision-making under pressure (Laarni *et al*., 2019).

Simultaneously, continuous psychophysiological monitoring enables the identification of individual stress and fatigue thresholds, allowing for adaptive task reallocation. This approach seeks to preserve both the physical and mental integrity of military personnel while maintaining operational efficiency (Veenstra *et al*., 2009).

In the domains of field medicine and special operations, portable or discreet biosensors, including wearable skin-adherent and even implantable devices, allow for the remote transmission of vital signs to command centers or rapid response teams. This capability significantly enhances real-time triage and medical intervention, particularly in hostile or remote environments where clinical decision-making must be swift and precise.

Although the integration of these sensors into standard military equipment - such as helmets, vests, and smart uniforms - is already underway, large-scale implementation continues to face logistical, ethical, and technical challenges. Addressing these barriers will require interdisciplinary solutions and the development of specific regulatory frameworks (Kumar, 2024).

4 Emerging Trends and Technologies

The evolution of biosensor technologies is increasingly shaped by the convergence of multiple disciplines, including biomedical engineering, artificial intelligence (AI), data science, nanotechnology, and wireless communications. This interdisciplinary integration is driving the development of a new generation of intelligent biosensors that are not only more accurate and compact but also context-aware, adaptive, and capable of real-time analysis in high-complexity operational environments.

4.1 Integration with Artificial Intelligence (AI) and Machine Learning

One of the most transformative trends in biosensor development is the integration of artificial intelligence (AI) and machine learning algorithms into biosensing platforms. By analyzing complex physiological patterns, AI enhances the predictive capabilities of biosensor data, enabling early detection of fatigue, stress, and musculoskeletal risk. For instance, supervised classifiers, such as support vector machines and logistic regression models, have demonstrated high accuracy in identifying cognitive and emotional states based on multimodal biometric datasets collected from military personnel during training (Aidman, 2020).

These computational tools enable the creation of adaptive feedback systems, in which biosensors function not merely as passive data collectors, but as integral components of decision-support infrastructures.

Such systems can autonomously alert commanders, healthcare professionals, or end users to emerging risk states, thereby facilitating timely and proactive interventions.

4.2 Battery-Free and Energy-Harvesting Biosensors

A new class of biosensors is emerging that operates independently of conventional batteries, utilizing energy-harvesting mechanisms such as thermoelectric generators (driven by body heat), piezoelectric materials (activated by movement), or inductive charging systems. These autonomous technologies significantly extend operational longevity and eliminate downtime associated with recharging, which is critical for long-duration missions and deployment in remote environments (Farzin *et al*., 2024).

Such features are particularly advantageous for discreet, continuous monitoring, especially in wearable and implantable devices.

4.3 Multimodal Platforms and Hybrid Sensors

Future biosensor systems are increasingly expected to adopt multimodal architectures, integrating physical signals (e.g., movement, posture), physiological indicators (e.g., heart rate variability, skin conductance), and environmental parameters (e.g., heat, altitude) into a single cohesive platform (Ray *et al*., 2019). These hybrid systems provide a holistic perspective on performance and risk, particularly relevant in military training environments where environmental stressors intersect with physical and cognitive demands.

For instance, combining inertial measurement units (IMUs) with EMG and EEG sensors allows for the simultaneous assessment of biomechanical and neuromechanical performance, neuromuscular control, and cognitive workload during complex task execution.

4.4 Miniaturization and Edge Computing

Advances in nanomaterials and microelectronics have driven the development of increasingly miniaturized, skin-conformable, and non-invasive biosensors. Wearable devices in the form of adhesive patches, smart textiles, or ingestible capsules are now capable of capturing high-resolution biomedical signals without compromising user mobility (Antony, 2024).

Consequently, many biosensor platforms are incorporating edge computing capabilities, enabling local data processing directly on the device rather than relying on cloud-based servers. This architectural shift reduces latency, enhances data privacy, and supports real-time anomaly detection, an essential feature for time-critical operational scenarios.

4.5 Brain-Computer Interfaces and Biointerfaces

The development of brain-computer interfaces (BCIs) represents a cutting-edge frontier in biosensor technology, with significant implications for both rehabilitation and operational enhancement. BCIs are capable of monitoring cortical activity to detect markers of mental fatigue, decision-making readiness, and cognitive overload (He *et al*., 2022). In tactical scenarios, these systems may evolve into command-enhancing tools, allowing for hands-free operation of equipment or the automatic transmission of cognitive state indicators to commanding officers.

Beyond BCIs, emerging Biointerfaces, such as electronic tattoos and epidermal devices, are redefining the physical interface between humans and machines. These technologies enable seamless integration of biosensors directly onto the skin, providing continuous data acquisition without discomfort or perceptibility.

4.6 Dual-Use Opportunities and Emerging Risks

The dual-use potential of biosensor technologies continues to expand significantly. On one hand, devices originally designed for applications in sports medicine or personalized healthcare can be readily adapted for monitoring the physiological and cognitive status of military personnel in real-world operational environments (Marson & Guimarães, 2021; Velayutham *et al*., 2024). Conversely, innovations emerging from the defense sector, engineered for extreme environments and real-time data transmission, can be translated into civilian contexts, supporting disaster response, elderly care, and occupational safety in high-risk industries (Velayutham *et al*., 2024). This cross-domain integration amplifies the social, economic, and operational value of biosensor solutions.

However, this convergence also introduces new challenges and risks. The fusion of biometric, behavioral, and geolocation data significantly increases user exposure to continuous surveillance and cyber-physical threats, necessitating the implementation of stringent data governance policies (Marson & Guimarães, 2021; Hu, 2013). Moreover, the persistent monitoring of individuals, especially within hierarchical institutions such as the military, raises critical ethical concerns related to personal autonomy, informed consent, and privacy preservation (Gomathy & Geetha, 2024).

Compounding these issues is the problem of technological fragmentation. As diverse manufacturers and platforms proliferate, the need for global standards becomes urgent to ensure device interoperability, secure communications, and the ethical use of sensitive information produced by these technologies (Gomathy & Geetha, 2024).

Together, these trends underscore the necessity of developing robust regulatory frameworks that balance incentives for innovation with protection for human dignity, operational integrity, and strategic autonomy.

5 Foresight Scenarios

This foresight study projects that between 2030 and 2040, the consolidation of next-generation biosensor technologies will occur in a systemic and integrated manner across both civilian healthcare infrastructures and military operational systems.

Based on the analysis of weak signals and emerging trends, three plausible scenarios - optimistic, realistic, and pessimistic - are proposed. These scenarios are constructed through the interplay of technological vectors, prospective regulatory frameworks, market dynamics, and potential strategic reconfigurations in the international landscape. Their purpose is to inform strategic planning and policy formulation by illustrating plausible outcomes shaped by present-day technological, ethical, and institutional decisions (Marson & Guimarães, 2021; Marson *et al.*, 2025).

5.1 Optimistic Scenario: Full Integration and Ethical Innovation

According to the analyses presented in this study, by 2040, biosensors will be universally adopted across the healthcare, sports, and defense sectors, supported by robust interoperability protocols and equitable access ensured through international standards. In this vision, wearable and implantable biosensors become foundational components of precision health systems, enabling early diagnosis, personalized treatment, and predictive monitoring of both physical and mental conditions.

In the military domain, biosensors will be fully embedded within next-generation soldier systems. Smart uniforms, helmets, and exoskeletons will incorporate real-time analytics to monitor fatigue, hydration levels, and injury risk.

Decision-support tools powered by artificial intelligence and informed by biosensor data will assist commanders in mission planning, resource allocation, and triage during operations. Ethical frameworks and global governance mechanisms will be in place to safeguard privacy, ensure informed consent, and prevent misuse of physiological data.

As a result, the dual-use innovations of this ecosystem will benefit disaster response teams, astronauts, elite athletes, and high-risk workers alike. Public-private partnerships, interdisciplinary investments in research, development, and innovation (RD&I), and transparent data governance practices will foster public trust and technological resilience.

5.2 Realistic Scenario: Gradual Adoption and Regulatory Delays

In this intermediate scenario - grounded in a critical assessment of technological trends and institutional dynamics - biosensor adoption progresses steadily, yet remains constrained by regulatory, ethical, and infrastructural barriers. Civilian healthcare systems prioritize these technologies for chronic disease monitoring and telehealth platforms, while the sports and occupational sectors employ them primarily for performance optimization and injury prevention.

In the military context, adoption occurs gradually, with applications concentrated in training, simulations, and non-lethal operations. Full integration into tactical equipment remains limited due to ongoing interoperability issues, logistical constraints, and inconsistent funding. Although physiological data are collected and analyzed, real-time utilization is hindered by a lack of on-device processing capacity and persistent cybersecurity concerns.

Legal and ethical issues gain prominence, particularly regarding data ownership, individual autonomy, and the acceptable boundaries of physiological surveillance. Regulatory bodies struggle to keep pace with the rapid evolution of biointerfaces and AI-mediated diagnostics. Meanwhile, international efforts to harmonize standards and address the dual-use implications of biosensors proceed unevenly, resulting in fragmented implementations across regions.

Despite these structural limitations, biosensors continue to offer meaningful advances in situational awareness and preventive health strategies, especially within special forces, elite athletic programs, and remote clinical settings. This scenario reflects a moderate technoscientific trajectory marked by localized gains, persistent institutional challenges, and the need for more effective global coordination.

5.3 Pessimistic Scenario: Surveillance Risks and Social Rejection

This scenario, derived from a critical extrapolation of dystopian trends and persistent regulatory gaps, envisions biosensors as negative symbols, associated with state surveillance, labor exploitation, and militarized control. Their widespread deployment across civilian and military settings results in the systemic erosion of privacy, normalization of biometric monitoring, and escalating ethical controversies over "physiological profiling": the practice of mapping neurophysiological patterns to categorize individuals into psychobiological profiles that may influence operational decisions, training paths, or promotion opportunities, often without transparency or informed consent.

Under authoritarian regimes, biosensors are weaponized to track dissidents, enforce disciplinary standards, and classify individuals based on neurophysiological traits. In the workplace, biometric surveillance practices are used to maximize productivity, frequently at the expense of worker autonomy, mental health, and well-being. In military contexts, compulsory biosensor monitoring raises concerns about coercion, physiological-psychological discrimination, and operational burnout.

The absence of robust international regulations exposes critical cyber-biological vulnerabilities. Biosensor networks become targets for manipulation, sabotage, or misinformation by strategic adversaries. Open-source platforms are exploited by biohackers and hostile actors to reverse-engineer military sensors, enabling illicit use and hybrid threats.

As public awareness of data exploitation grows, societal rejection of biosensors in civilian environments intensifies. Governments respond with reactive and restrictive measures that stifle innovation and deepen geopolitical divides concerning the governance of bio-integrated technologies. This scenario serves as a cautionary tale about the consequences of lacking ethical safeguards, unchecked data power concentration, and the dysfunctional use of sensitive technologies within imbalanced institutional contexts.

5.4 Strategic Implications

These scenarios underscore the urgent need to establish proactive, ethical, and collaborative governance models for the development and application of biosensor technologies. The future trajectory of these innovations is not determined by technical capabilities alone; rather, it will be fundamentally shaped by decisions made within regulatory, scientific, and operational spheres over the coming decade.

Strategic planning aimed at integrating biosensors into civilian and military systems must prioritize continuous investment in technological architectures that embed security and ethics by design. This includes the development of technical standards that ensure interoperability across platforms and safeguard the integrity of sensitive personal data. Additionally, it is essential to incorporate foresight analysis into national planning efforts across defense and public health sectors, thereby aligning innovation with social responsibility and institutional preparedness.

Finally, effective mechanisms must be established to mitigate the risks associated with dual-use technologies and to prevent misuse that could compromise fundamental rights or national strategic interests.

In summary, biosensors represent both an opportunity and a risk. The way this balance is managed will determine whether these technologies enhance resilience and human performance or undermine autonomy and social trust.

6. Civil-Military Convergence and Policy Implications

The convergence of civilian and military applications of biosensor technologies marks a critical inflection point for public policy in science and technology. Although biosensors originated within clinical and biomedical domains, their increasing adoption in defense environments reflects a broader pattern of dual-use innovation, in which tools initially developed for health and performance monitoring are repurposed for surveillance, operational control, and force optimization. This convergence offers opportunities for cross-sectoral synergy, y*et al*so presents significant challenges concerning ethics, security, data governance, and regulatory alignment (Silva, 2022; Marson *et al*., 2024).

6.1 Regulation of Dual-Use Technologies

As biosensor technologies continue to mature, their dual-use nature raises critical concerns regarding export control and international regulation. Devices capable of monitoring cognitive readiness, stress biomarkers, or neurophysiological states may be deployed in benign public health contexts or, alternatively, in coercive military regimes.

International agreements such as the Wassenaar Arrangement (Davis, 1996) and other export control regimes may require revision to encompass bio-integrated systems and AI-enhanced physiological monitoring tools, which currently reside within regulatory grey zones (Kim, 2022).

Technology transfer between civilian and military sectors, whether through government partnerships, academic collaborations, or private Research, Development and Innovation (RD&I) programs, should be subject to clear oversight mechanisms. The establishment of public registries for dual-use technologies, transparent licensing agreements, and ethics review committees can help mitigate the risks of misuse or unintended repurposing.

6.2 Civil-Military Cooperation and Technology Transfer

Successful innovation ecosystems increasingly rely on collaborative structures in which military institutions benefit from commercial advancements in biosensor technologies, while civilian sectors adopt robust systems initially tested under extreme operational conditions. Military RD&I programs frequently serve as incubators for technologies that later transition into civilian applications, such as occupational safety, eldercare, and athletic performance optimization.

To ensure ethical and responsible technology transfer, formal agreements must include provisions on data protection, usage limitations, and public accountability. Collaborative frameworks, such as innovation hubs and joint laboratories involving the armed forces and academic institutions, should be encouraged and operated under democratic oversight. These partnerships not only enhance technological development but also promote transparency and public trust in dual-use applications.

6.3 Ethical, Legal, and Social Implications

The proliferation of biosensors presents a range of urgent ethical concerns. In civilian settings, users typically provide informed consent for data collection, often for therapeutic or performance enhancement purposes (Bouderhem, 2024). In military environments, however, informed consent becomes more complex, particularly within rigid hierarchical structures or in combat zones where individual autonomy may be constrained.

The application of biosensors in predictive analytics, such as identifying potential operational failures, signs of insubordination, or imminent psychological breakdowns, raises significant ethical questions. There is a growing concern about the potential use of algorithmically generated profiles to justify preemptive disciplinary actions or to exclude individuals based on predictive indicators. This practice risks infringing on fundamental rights, especially in command-driven systems where the boundary between functional monitoring and coercive surveillance can be easily blurred (Rausch *et al*., 2022).

Given these challenges, ethical frameworks governing biosensor deployment must be sufficiently robust to define the scope and limits of real-time monitoring, ensure individuals retain the right to refuse tracking or request the anonymization of their biometric and cognitive data, and establish safeguards against algorithmic bias, institutional coercion, and cyber vulnerabilities arising from the automated collection and interpretation of sensitive information.

6.4 Data Privacy and Cybersecurity Risks

Data generated by biosensors are highly sensitive, revealing insights into an individual's mental state, medical conditions, and behavioral patterns (Marson & Guimarães, 2021). In both civilian and military settings, such data simultaneously represent strategic assets and critical vulnerabilities. Without robust encryption and authentication protocols, biosensor systems are susceptible to interception, data falsification, and malicious manipulation (Sedenberg *et al*., 2017).

In defense applications, cyber-biological attacks may involve sensor communication jamming, injection of false data to disrupt operational decision-making, or real-time interception of physiological metrics for geolocation and tracking of personnel (Marson & Guimarães, 2021). In the civilian sphere, risks include unauthorized surveillance, commercial exploitation of data by third parties, and discriminatory use of biometric information by insurers or employers.

National security frameworks must acknowledge biosensor networks as strategic components of critical digital infrastructure, given their potential to impact information integrity, data sovereignty, and the operational reliability of civil and military systems. This recognition demands the implementation of security architectures that ensure secure sensor communication through continuous authentication, stringent identity verification, and network segmentation strategies (Gayathri & Sathya, 2015).

Additionally, there is an urgent need to promote the development and adoption of cybersecurity certification standards specifically tailored to wearable and implantable medical devices. These standards should ensure compliance with stringent requirements for security, interoperability, and resilience against cyber-physical threats.

6.5 Strategic Autonomy and National Readiness

Excessive reliance on foreign biosensor manufacturers or proprietary data management platforms poses a strategic risk to national autonomy, with direct implications for sovereignty in both civilian and military domains. To mitigate this risk, governments must actively promote domestic innovation capabilities, encourage the adoption of open technological standards, and enforce data storage protocols aligned with principles of digital sovereignty (Bruckner-Lea, 2004; Graham & Sabelnikov, 2004).

This study projects that within the defense context, military readiness strategies must include the development of contingency plans for potential biosensor system failures. These should encompass the deployment of redundant physiological monitoring methods to ensure continuity in the collection and analysis of mission-critical data.

Furthermore, the ethical training of commanders and officers responsible for data management is essential to uphold the integrity, responsible use, and protection of sensitive information in high-complexity operations.

In sum, the civil-military convergence in the biosensor domain is both inevitable and transformative. Leveraging its benefits while mitigating associated risks will require forward-looking legal frameworks, interdisciplinary regulatory innovation, and sustained multisectoral dialogue. These measures are essential to ensure that biosensors enhance human performance without compromising individual rights, public trust, or national security.

7 Research, Development, and Innovation (RD&I) and Interdisciplinary Collaboration

The dual-use nature and rapid pace of innovation in biosensor technologies demand proactive, coordinated, and ethically grounded approaches to research, development, deployment, and governance. This section outlines key recommendations designed to guide both civilian and military sectors toward the sustainable, secure, and effective integration of biosensors.

To fully realize the transformative potential of biosensors, continuous investment is essential in both basic and applied research, particularly at the intersection of biomedical engineering, artificial intelligence, and operational sciences. As Marson *et al*. (2023) argue, governments, defense agencies, and the private sector should prioritize:

a) Public-private partnerships for the development of biosensor systems tailored to real-world needs;

b) Interdisciplinary RD&I centers integrating expertise in medicine, biomechanics, neuroscience, and data science; and

c) Longitudinal field studies in both civilian and military contexts to validate the efficacy, usability, and long-term impact of these technologies.

7.1 Standards and Protocols for Interoperability and Privacy

Given the fragmentation and rapid technological evolution in biosensor development, it is imperative to establish national and international technical standards that ensure system interoperability, data consistency, and secure device communication (Nomula, 2024). Standardization efforts should address data formatting, sensor calibration protocols, and application programming interfaces (APIs) responsible for integrating diverse technologies. Moreover, cybersecurity and encryption protocols must be embedded to guarantee the confidentiality and integrity of data during transmission and storage (de Lacerda Filho *et al*., 2020).

Regulatory bodies should foster the creation of controlled experimental environments, or regulatory sandboxes, in which developers can test emerging technologies under existing legal and ethical frameworks. Such mechanisms promote responsible and secure innovation.

7.2 Ethical Implementation and Regulatory Frameworks for Dual-Use Technologies

The ethical deployment of biosensor technologies, especially in coercive or hierarchical environments such as the military, requires the construction of robust governance structures that safeguard individual rights and ensure the responsible use of collected data (Bouderhem, 2024).

National governments and international coalitions must establish bioethics committees to critically evaluate the use of biosensors in operational and healthcare settings. Additionally, regulatory frameworks must be developed to monitor and control the transfer of dual-use technologies, preventing their repurposing for malicious ends (Kolstoe, 2021).

Specific codes of conduct should be designed for commanders, healthcare professionals, and data analysts to prevent misuse, discriminatory practices, or abusive surveillance. These governance mechanisms must remain adaptive and undergo periodic revision to remain aligned with technological advances and the evolving political-institutional landscape in which biosensors are applied.

7.3 Capacity Building in Civilian and Military Sectors

Maximizing the value of biosensor technologies requires more than technical infrastructure; it also demands strengthened professional capacity to correctly operate, interpret, and apply biosensor-generated data in decision-making processes (Bruckner-Lea, 2004). Continuous education and training programs are essential for healthcare providers, sports scientists, and military instructors in the strategic use of biosensor data.

In the military context, such capacity building includes training soldiers and commanders to interpret physiological alerts and integrate these insights into tactical planning, without becoming overly reliant on technology or misinterpreting the signals (Velayutham *et al*., 2024).).

7.4 Inclusive Innovation and Equity

Ensuring that the benefits of biosensor technologies are accessible to all segments of society, not restricted to elite institutions or armed forces, requires public policies guided by principles of equity, affordability, and user-centered development.

This includes promoting the design of low-cost systems for public health and resource-constrained environments, encouraging community-based testing to adapt technologies to diverse populations and cultural contexts, and establishing mechanisms to monitor and mitigate access disparities. Special attention must be directed toward socially vulnerable groups, conscripted military personnel, and populations in remote or underserved regions (Warfade *et al*., 2025).

These recommendations aim to balance innovation with accountability. By institutionalizing ethical foresight, technical rigor, and inclusive governance, civilian and military institutions can ensure that biosensor technologies support human empowerment, operational readiness, and the protection of fundamental rights within an increasingly complex technological landscape (Papaioannou, 2018).

8 Final Considerations

Biosensor technologies stand at the forefront of a profound transformation in how human health, physical performance, and cognitive states are measured, monitored, and optimized. As demonstrated throughout this foresight study, the convergence of biosensors with artificial intelligence, wearable systems, and real-time analytics has opened a new frontier across both civilian and military domains.

Evolving from their initial applications in clinical diagnostics and sports science, biosensors have become powerful tools capable of supporting operational decision-making, enhancing performance, and enabling preventive health surveillance strategies. Their dual-use nature - simultaneously applicable in healthcare systems and defense operations - presents both strategic opportunities and complex regulatory challenges. In military contexts, biosensors can enhance mission readiness, mitigate injury risk, and provide early warnings of fatigue or physiological overload. In civilian sectors, these same technologies hold promises for advancing personalized medicine, managing chronic diseases, and improving workplace safety.

This study offers a comprehensive assessment of current technologies, emerging trends, and cross-sectoral applications. Methodological tools such as horizon scanning, Technology Readiness Level (TRL) analysis, and foresight scenario modeling were used to delineate three plausible futures: (i) an optimistic scenario characterized by ethical integration and global interoperability; (ii) a realistic trajectory of fragmented adoption and regulatory lag; and (iii) a critical scenario defined by surveillance risks and social rejection.

To move toward the most desirable scenario, several key actions are required: increased investment in interdisciplinary RD&I, the establishment of robust privacy and cybersecurity standards, the development of ethical and targeted regulatory frameworks for dual-use technologies, and the promotion of both technical and critical capacity-building among all stakeholders.

Most importantly, biosensor implementation must prioritize the preservation of individual autonomy, the protection of privacy, and the promotion of equity. In military settings, this entails respecting the physiological and psychological boundaries of service members. In civilian contexts, it requires ensuring that the benefits of these technologies are equitably distributed across diverse social groups and geographic regions.

As the coming decades unfold, the strategic significance of biosensors is expected to grow. Those who proactively anticipate technological trajectories, institute ethical safeguards, and invest in inclusive innovation will be best positioned to harness the full potential of these systems. This foresight study thus serves both as a roadmap and a call to action, inviting policymakers, scientists, and institutional leaders to shape the future of biosensor technologies in a secure, ethical, and resilient manner.

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