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CONNECTING THE HUMAN TO THE DIGITAL: EXPLORING THE INTERNET OF BODIES AND ITS DEVICE CATEGORIES

CONECTANDO O SER HUMANO AO MUNDO DIGITAL: EXPLORANDO A INTERNET DOS CORPOS E SUAS CATEGORIAS DE DISPOSITIVOS

CONECTANDO LO HUMANO CON LO DIGITAL: UNA EXPLORACIÓN DEL INTERNET DE LOS CUERPOS Y SUS CATEGORÍAS DE DISPOSITIVOS

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ABSTRACT

The Internet of Bodies (IoB) represents an emerging technological frontier that extends digital connectivity directly into the human domain, integrating the body into information networks. This article explores the IoB and its various categories of devices, which include wearables, injectables, ingestibles, implantables, and integrated devices. Each type of device plays a unique role in the collection and transmission of physiological and behavioral data, ranging from external health monitors to advanced neural interfaces. The objective of this work is to analyze the transformative potential of the IoB, particularly in health and well-being, where continuous monitoring and personalized intervention can revolutionize disease prevention, diagnosis, and treatment. We discuss how wearable devices can optimize performance and safety, while injectable, ingestible, and implantable devices offer new approaches to internal diagnostics and therapies. However, the proliferation of the IoB poses significant challenges. The research addresses complex data privacy issues, given the sensitive nature of the biometric information collected, and critical cybersecurity concerns, which can have critical implications for individuals' well-being and lives. Additionally, ethical and governance considerations are examined, including consent, autonomy, and the risk of

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algorithmic bias. We conclude that, although IoB promises unprecedented advances, its development and implementation require a robust regulatory framework and a multidisciplinary approach that balances innovation with individual and social protection. Collaboration among stakeholders is essential to ensure a future where IoB benefits humanity safely and ethically.
KEYWORDS: Wearable sensors; Injectable sensors; Ingestible sensors; Implantable sensors; Integrated sensors.

RESUMO
A Internet dos Corpos (IoB) representa uma fronteira tecnológica emergente que estende a conectividade digital diretamente ao domínio humano, integrando o corpo em redes de informação. Este artigo explora a IoB e suas diversas categorias de dispositivos, que incluem vestíveis, injetáveis**,** ingeríveis**,** implantáveis **e** integrados. Cada tipo de dispositivo desempenha um papel único na coleta e transmissão de dados fisiológicos e comportamentais, desde monitores de saúde externos até interfaces neurais avançadas. O objetivo deste trabalho é analisar o potencial transformador da IoB, particularmente na saúde e bem-estar, onde o monitoramento contínuo e a intervenção personalizada podem revolucionar a prevenção, diagnóstico e tratamento de doenças. Discutimos como dispositivos vestíveis podem otimizar o desempenho e a segurança, enquanto os injetáveis, ingeríveis e implantáveis oferecem novas abordagens para diagnóstico interno e terapias. No entanto, a proliferação da IoB levanta desafios significativos. A pesquisa aborda as complexas questões de privacidade de dados, dada a natureza sensível das informações biométricas coletadas, e as imperativas preocupações com a segurança cibernética, que podem ter implicações críticas para a integridade e a vida dos indivíduos. Além disso, são examinadas as considerações éticas e de governança, incluindo consentimento, autonomia e o risco de viés algorítmico. Concluímos que, embora a IoB prometa avanços sem precedentes, seu desenvolvimento e implementação exigem um arcabouço regulatório robusto e uma abordagem multidisciplinar que equilibre inovação com proteção individual e social. A colaboração entre stakeholders é essencial para garantir um futuro onde a IoB beneficie a humanidade de forma segura e ética.
PALAVRAS CHAVE: Sensores vestíveis; Sensores injetáveis; Sensores ingeríveis; Sonsores implantáveis; Sensores integrados.

RESUMEN
El Internet de los Cuerpos (IoB) representa una frontera tecnológica emergente que extiende la conectividad digital directamente al ámbito humano, integrando el cuerpo en las redes de información. Este artículo analiza el IoB y sus diversas categorías de dispositivos, que incluyen dispositivos portátiles (wearables), inyectables, ingeribles, implantables e integrados. Cada tipo de dispositivo desempeña un papel único en la recopilación y transmisión de datos fisiológicos y conductuales, desde monitores de salud externos hasta interfaces neuronales

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avanzadas. El objetivo de este trabajo es analizar el potencial transformador de la IoB, especialmente en el ámbito de la salud y el bienestar, donde la monitorización continua y la intervención personalizada pueden revolucionar la prevención, el diagnóstico y el tratamiento de enfermedades. Analizamos cómo los dispositivos wearables pueden optimizar el rendimiento y la seguridad, mientras que los inyectables, ingeribles e implantables ofrecen nuevos enfoques para el diagnóstico interno y las terapias. Sin embargo, la proliferación del IoB plantea retos importantes. La investigación aborda las complejas cuestiones relacionadas con la privacidad de los datos, dada la naturaleza sensible de la información biométrica recopilada, y las preocupaciones imperativas en materia de ciberseguridad, que pueden tener implicaciones críticas para la integridad y la vida de las personas. Además, se examinan las consideraciones éticas y de gobernanza, incluyendo el consentimiento, la autonomía y el riesgo de sesgo algorítmico. Concluimos que, aunque el IoB promete avances sin precedentes, su desarrollo e implementación exigen un marco regulatorio sólido y un enfoque multidisciplinar que equilibre la innovación con la protección individual y social. La colaboración entre las partes interesadas es esencial para garantizar un futuro en el que el IoB beneficie a la humanidad de forma segura y ética.
PALABRAS CLAVE: Sensores vestibles; Sensores inyectables; Sensores ingeribles; Sensores implantables; Sensores integrados.

1. INTRODUCTION

Technological evolution has been marked by the ubiquitous integration of computer systems into everyday human life, consolidated under the Internet of Things (IoT). Currently, connectivity transcends inanimate objects to merge directly with human biology. This new stage is called the Internet of Bodies (IoB), an ecosystem where smart devices are worn, injected, implanted, ingested, or attached to the body, enabling the monitoring and transmission of biometric data in real time (CELIK, 2022). While the IoT revolutionized interaction with the environment, the IoB proposes a redefinition of physical and digital identity, transforming the human body into an active node within a global network (MATWYSHYN, 2019).

Despite promises of advances in health and productivity, the implementation of the IoB raises critical ethical, legal, and security issues. The sensitive nature of the data collected—heart rates, sleep patterns, and brain waves—makes privacy vulnerable. Unlike a password, biometric data is intrinsic to the human being and,

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once compromised, cannot be altered, increasing the risks of surveillance and algorithmic discrimination (EL-KHOURY, 2021). Furthermore, cybersecurity is vital; a vulnerability in a connected device poses a direct threat to the user's physical well-being (AMATO, 2021; SANTOS, 2025).

In this context, data governance and legal regulation face the challenge of keeping pace with biotechnological innovations. Current legal frameworks prove insufficient to address the complexity of "ownership of the digital body" and the individual's autonomy over their biometric data streams (XIAO, 2020). Therefore, it is imperative to analyze the implications of the IoB from a multidisciplinary perspective, considering technical feasibility and socio-technical impacts. This article explores these dimensions, discussing the benefits and risks inherent in this new frontier of human connectivity.

2. METHODOLOGY

The study was conducted using the qualitative method as described by Martinelli (1999), who defined the qualitative research method as an approach that employs investigative procedures to collect and analyze data in a descriptive and interpretive manner, seeking to understand the phenomena studied in their complexity and particularities.

The methodological approach adopted was narrative in nature, employing a qualitative, interpretive, descriptive, and exploratory methodology, and included a literature review, which consisted of reviewing the main studies already conducted on the topic. The literature review was conducted using indexed scientific databases such as Google Scholar, Scientific Electronic Library Online (Scielo), Latin American and Caribbean Health Sciences Literature (LILACS), and the Medical Literature Analysis and Retrieval System Online (MEDLINE). For the search, we focused on scientific articles published in Portuguese and English between 2015 and 2026, using 72 articles as shown in the flowchart (Figure 1). The inclusion criteria focused on studies that directly address the Internet of Bodies, its medical applications, and ethical implications,

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using the following keywords: Internet of Bodies; Wearable Sensors; Injectable Sensors; Ingestible Sensors; Implantable Sensors; Integrated Sensors; and Body Intelligence. This selection is based on adherence to rigorous quality criteria in these databases, which ensure the credibility and reliability of the information provided.

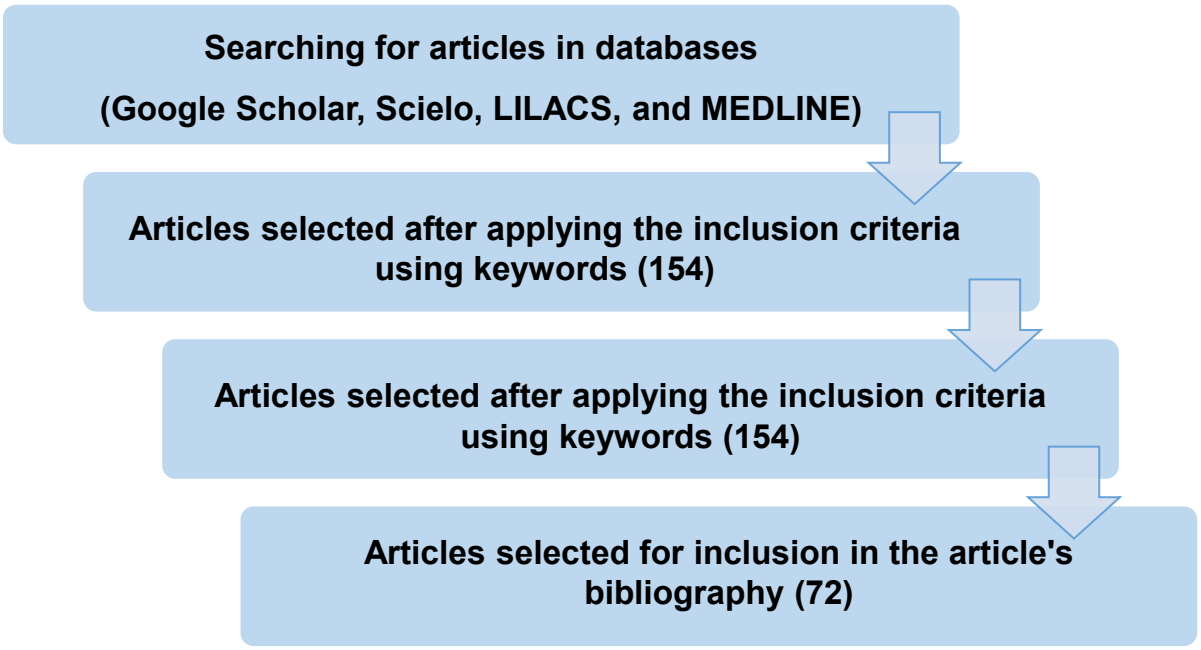

Figure 1. Study flowchart.

Finally, after data collection, content analysis was conducted, which was also guided by the subjectivist method. This analysis took into account the research objectives and the hypotheses raised, resulting in the final development of this study, grounded in the reflections made throughout the process.

3. THE INTERNET OF BODIES AND THE INTELLIGENCE OF BODIES

IoB is technically defined as an evolution of the IoT consisting of a network of devices interconnected with the human body through clothing, infusion, ingestion,

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implantation, or integration, capable of collecting and transmitting physiological, biometric, and behavioral data (Figure 2). These devices, which include wearable, injectable, ingestible, implantable, and integrated sensors, establish a direct interface between the body and the digital infrastructure, enabling continuous monitoring and analysis of a wide range of biological variables (CELIK, 2022). IoB operates through intra- and inter-body communications, using the body itself as a data transmission channel or conventional wireless networks to connect to external systems, such as the cloud. This architecture transforms the human body into a data platform, enabling applications ranging from remote health monitoring to brain-computer interfaces, while simultaneously introducing significant challenges in terms of security, privacy, and data integrity (BODDINGTON G, 2021; MAZZEO, 2025).

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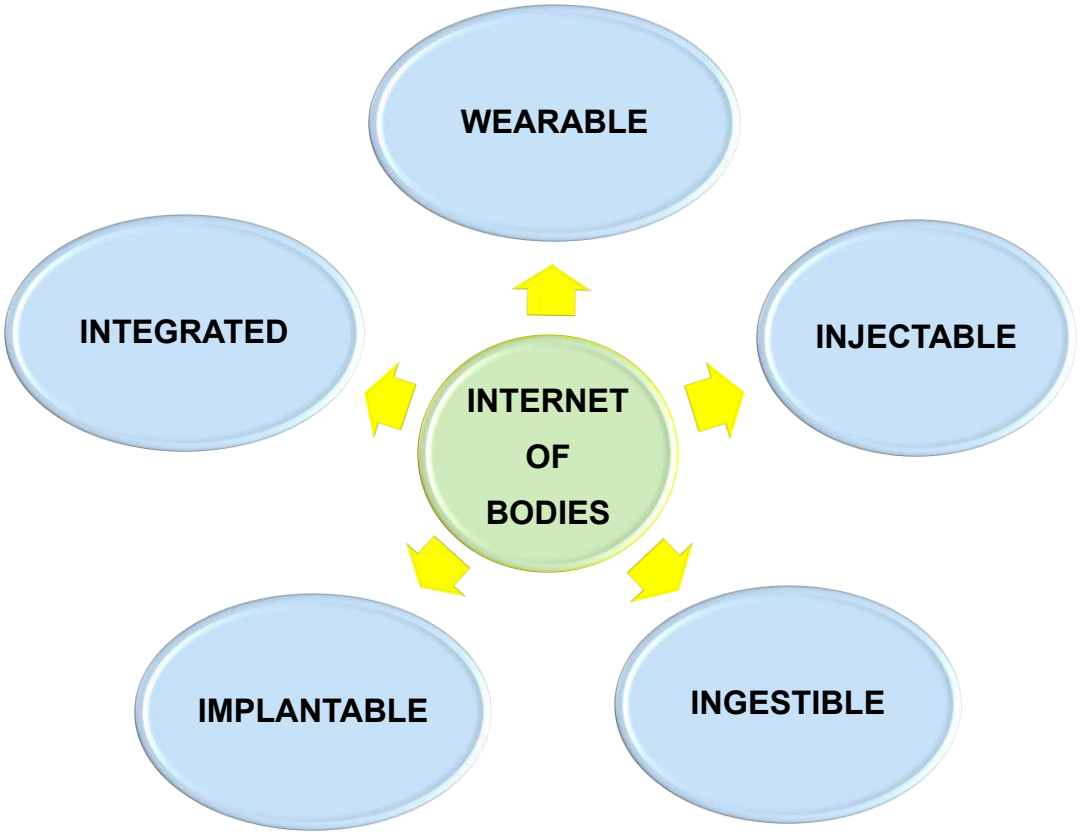

Figure 2. Methods for attaching sensors to the human body.

Unlike the IoT, where security breaches can result in property damage, IoB technologies have the potential to cause direct physical harm to humans. This interconnection raises complex questions about human autonomy and self-governance, challenging established social norms and values.

Artificial Intelligence of the Body (AIoB) represents the advanced convergence between IoB and machine learning algorithms, defined as the ability of cybernetic systems to process, interpret, and act autonomously on massive streams of biological and behavioral data captured through devices that are wearable, injectable, ingestible, implanted, or integrated into the human body. Technically, this intelligence goes beyond simple data collection, operating under the paradigm of embodied intelligence, in which artificial cognition is shaped by the dynamic

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interaction between the device's morphology, the physical environment, and the host's biological system (LIU, 2025). This ecosystem enables the creation of highly accurate predictive models for human health, capable of identifying subclinical pathological patterns and optimizing physiological functions in real time through closed-loop feedback mechanisms (BIBRI, 2023; CHATTERJEE, 2023). However, AIoB introduces ontological complexity by transforming the body into a living computational platform, requiring robust security architectures to mitigate risks of neural or physiological manipulation, as well as demanding new governance structures to protect individuals' biological autonomy and neurocognitive privacy (MATWYSHYN, 2019). This integration definitively redefines the boundary between the biological and the digital.

The integration of AI allows this raw data to be processed and transformed into actionable insights, enabling predictive health monitoring, personalized interventions, and the optimization of individual well-being. AIoB not only facilitates proactive health monitoring but also redefines human interaction with technology, fostering a symbiosis where the body and artificial intelligence collaborate to enhance human capabilities and quality of life, although it raises significant ethical and privacy concerns regarding the autonomy and integrity of bodily data (BIBRI, 2023).

WEARABLE SENSORS

In the context of the Internet of Bodies (IoB), wearable devices—also known as external devices—are defined as miniaturized, low-power embedded systems designed to be worn on the surface of the human body or integrated into clothing. Thus, we can conclude that Body Sensor Networks (BSNs) have evolved into complex systems that leverage advancements in microelectronics and wireless communication to establish ubiquitous connectivity between the individual and the digital infrastructure (GRAVINA, 2020). These sensors act as the primary interface of the IoB, capturing vital signs that enable the monitoring of physical and mental

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health states, transforming the body into a source of real-time data that can be aggregated and analyzed in cloud environments for personalized interventions. This approach enables proactive monitoring, which is especially useful for the elderly and patients with chronic conditions. Thus, wearable sensors not only facilitate the transition to preventive and precision medicine but also redefine the interaction between technology and human biology, consolidating the concept of a permanently connected and monitored body (LIU, 2025).

External devices, classified as first-generation and the most popular in society, encourage physical activity and promote healthy habits by tracking metrics such as step count, calorie expenditure, and sleep quality (SARAVANAKUMAR, 2022). Among these are smartwatches, fitness trackers, heart rate monitors, smart glasses, smart health monitoring rings, headphones, and smart clothing (smart textiles) with built-in sensors for monitoring posture, muscle activity, and vital signs (KHAN, 2021; MAZZEO, 2025). Sensors for specific chronic conditions such as heart disease, hypertension, and diabetes—classified as portable biomedical sensors for constant and remote monitoring—enable continuous glucose monitoring (CGM) for diabetics and the performance of electrocardiograms (ECG), as well as measuring oxygen saturation, blood pressure, and body temperature, which allows patients to benefit from early interventions. External devices can be used in telemedicine and remote care, enabling data collection for remote medical consultations (GHIWAA, 2024; MAZZEO, 2025).

INJECTABLE SENSORS

Injectable sensors are emerging as a promising technology, enabling continuous and minimally invasive monitoring of internal biomarkers. These devices, often on a micro- or nano-scale, are introduced into the body via tissue injection using syringes or hypodermic needles, where they interact with the biological environment to detect and quantify specific analytes. Unlike surgical implants, these sensors have unique shapes, such as wires or flexible microparticles, enabling

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continuous monitoring of vital parameters—such as glucose, oxygenation, and neural activity—in deep organs with minimal trauma (KIOURTI, 2017; JUNG, 2020). Connectivity to the IoB network enables real-time data transmission to digital health platforms, facilitating early diagnoses and personalized interventions. However, large-scale implementation faces significant challenges related to biocompatibility, cybersecurity, and energy autonomy (CELIK, 2022).

In general terms, the sensor consists of three layers: 1 – Acquisition Layer (In-Body): the injected sensor remains inert within the tissue, with no internal electronic components or batteries, which eliminates the risk of immune rejection and mechanical failure. Detection occurs passively, depending solely on the chemical interaction between the analyte and the hydrogel (KIOURTI, 2017); 2 – Transmission Layer (On-Body): An external optical reader, positioned on the skin, emits pulses of infrared light that excite the sensor. The fluorescent response is captured by the reader, which converts the optical signal into digital data. This communication occurs via low-energy protocols, such as Bluetooth Low Energy (BLE), sending the information to a smartphone or gateway (CELIK, 2022); and 3 - Analysis Layer (Cloud): The data is transmitted to a digital health platform, where artificial intelligence algorithms analyze oxygenation trends. If levels fall below a critical threshold, the system generates automatic alerts for the medical team, enabling preventive interventions before irreversible tissue damage occurs (CHATTERJEE, 2023).

IoB transforms passive monitoring into proactive and predictive health management. The ability to “inject” intelligence into deep tissues allows doctors to visualize the body’s internal dynamics as easily as they monitor heart rate on a smartwatch. The integration of this data into electronic health records and clinical decision support systems represents the pinnacle of convergence between biotechnology and computer science (MAZZEO, 2025).

A notable example of the action of injectable sensors is the development of hydrogel-based biosensors. These biocompatible hydrogels are designed to

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encapsulate sensitive elements, such as fluorophores or enzymes, that react to changes in the concentration of substances like glucose, oxygen, or lactate (LYU, 2023). When injected into subcutaneous tissue, for example, the hydrogel stabilizes and the sensing element emits a signal (optical or electrical) that varies in intensity or frequency according to the concentration of the target biomarker. An external device, such as an adhesive patch or a smartwatch, acts as a reader, capturing this signal and converting it into digital data. This data is then transmitted via wireless communication (Bluetooth, Wi-Fi, or 5G) to a smartphone, a local gateway, or directly to the cloud, integrating with the IoB network for analysis, storage, and, if necessary, medical alerts (ESTRELA, 2023).

One practical application is injectable microsensors for continuous monitoring of tissue oxygenation, such as the Lumee Oxygen platform. These sensors integrate into the tissue without causing a significant inflammatory response and emit fluorescence proportional to the oxygen concentration, enabling real-time assessment of perfusion in patients with chronic wounds or ischemic conditions (NICHOLS, 2018). Similarly, research is advancing on injectable hydrogel sensors for long-term glucose monitoring, using polymeric dot transducers (Pdots) to offer an alternative to traditional capillary puncture methods (LIU, 2022). The ability to provide physiological data in real time and continuously positions injectable sensors as crucial tools for personalized medicine, early diagnosis, and proactive health management in the IoB landscape.

INGESTIBLE SENSORS

Swallowable sensors, often referred to as “smart pills” or “electronic capsules,” represent a key category of devices in the Internet of Bodies (IoB). Ingestible sensors act as tiny mobile laboratories, designed to be swallowed and navigate the gastrointestinal tract, where they perform diagnostics, monitor physiological parameters, or verify medication adherence (STEIGER, 2019).

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A prominent example of these sensors' function is the monitoring of medication adherence. Devices such as those developed by Proteus Digital Health incorporate a tiny sensor (the size of a grain of sand) into a pill. After ingestion, the sensor is activated by gastric fluids and generates a low-power electrical signal that is transmitted through the body's tissues to an adhesive patch placed on the patient's skin (HAFEZI, 2015). This patch, which functions as a gateway, records the exact time the medication was taken and can collect other physiological data, such as heart rate and activity patterns. The information is then transmitted via Bluetooth to a smartphone app or directly to a cloud platform, allowing patients, caregivers, and healthcare professionals to monitor treatment adherence in real time and intervene when necessary (ALIPOUR, 2020).

Another significant example is the use of ingestible sensors for gastrointestinal diagnosis. The SmartPill™, for example, is a wireless capsule that, once swallowed, measures pH, temperature, and pressure throughout the gastrointestinal tract. This data is crucial for assessing gastric motility and intestinal transit time, as well as for diagnosing conditions such as gastroparesis or chronic constipation (MULES, 2026). The capsule continuously transmits this data via radio frequency to an external recorder worn by the patient. The data is subsequently downloaded and analyzed by a physician, providing a detailed view of the digestive system's functioning without the need for invasive procedures such as traditional endoscopy (STEIGER, 2019).

This technology is particularly valuable for monitoring adherence to medication regimens, especially in conditions where compliance is crucial, such as psychiatric disorders. By providing objective confirmation that the medication has been taken, digital pills allow doctors and caregivers to track the patient's progress and adjust treatment plans as needed, although they raise important considerations regarding privacy and data security (LITVINOVA, 2023).

These examples illustrate how ingestible sensors are transforming health monitoring by providing accurate, real-time internal data that is essential for

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personalized medicine and proactive disease management. The integration of these devices into the IoB enables continuous connectivity, facilitating clinical decision-making and empowering individuals to manage their own health (DATTA, 2020).

IMPLANTABLE SENSORS

Implantable sensors are emerging as crucial technologies, defined as biomedical devices surgically inserted into the body to continuously monitor physiological and biochemical parameters in vivo, remaining in the body for long periods of time. Unlike external wearables, implantable sensors offer significant advantages, such as greater precision in data collection, uninterrupted monitoring without the need for active user engagement, and direct access to internal tissues and fluids, enabling early detection of anomalies and real-time intervention (YOGEV, 2023).

These sensors cover a wide range of applications, including the monitoring of vital signs and electrophysiological activity (YOGEV, 2023). The integration of these devices into the IoB enables the creation of a Health 5.0 ecosystem, focused on smart disease management, virtual care, and personalized health management, including: 1 - Implantable nanoelectronics, which utilize sub-millimeter-sized devices to minimize invasiveness; 2 - Body-to-cloud communication aimed at 5G connectivity and integration with the medical cloud for real-time data updates; 3 - Autonomous feedback systems in which devices not only monitor but also perform therapeutic actions based on collected data; and 4 - Integration with artificial intelligence through which algorithms personalize treatments based on the patient's physiological history (MAZZEO, 2025).

One example of a critical application is found in smart pacemakers and implantable cardioverter-defibrillators (ICDs). Traditionally, these devices are surgically implanted to regulate heart rhythm or deliver electrical shocks in the event of dangerous arrhythmias. With the evolution toward IoB, these devices now incorporate advanced sensing and communication capabilities. Electrodes

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implanted in the heart continuously monitor electrical activity, and any irregularities are automatically detected and treated. More importantly, IoB functionality enables the wireless transmission of detailed reports on cardiac events to clinics and physicians. This remote telemetry enables healthcare professionals to assess the device's performance and the patient's cardiac health from a distance, allowing for rapid, personalized interventions before symptoms worsen, significantly improving patients' quality of life and survival (LEE, 2025).

Despite their great potential, the clinical adoption of implantable sensors faces complex challenges. Issues such as biocompatibility (to prevent immune rejection), power supply (limited by battery capacity and the need for energy harvesting), data security (protection against unauthorized access in an environment with limited computational resources), miniaturization, and ethical and legal considerations are significant barriers driving current research (YOGEV, 2023; MAZZEO, 2025). Overcoming these obstacles is essential for implantable sensors to transform medicine, offering more accurate diagnoses and more effective therapies, and consolidating the role of the human body as an active digital interface (BODDINGTON, 2021; MAZZEO, 2025).

The role of implantable sensors in the IoB goes beyond mere monitoring, enabling healthcare systems to provide more predictive, preventive, and personalized care. Continuous innovation in these devices, coupled with improvements in communication infrastructure and data analysis, promises to revolutionize medicine, making the human body a rich source of information for optimizing health and well-being (MAZZEO, 2025).

INTEGRATED SENSORS

In the emerging IoB ecosystem, integrated sensors constitute the fundamental infrastructure that enables an unprecedented convergence between the biological organism and digital networks. Integrated devices, also known as embedded devices or those embedded in body tissue at the cellular or molecular

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level through permanent or semi-permanent insertion, represent the cutting edge of this technological innovation. By being integrated directly into tissues or cells, these devices operate in real time to collect biological data, administer therapies, monitor, or even modulate physiological processes.

Unlike conventional IoT sensors, sensors integrated into the IoB operate in close symbiosis with the host, transforming the human body into an active data node that generates continuous information feeding Body Area Networks (BANs) and enabling direct communication between bodies (Body-to-Body - B2B) (CHATTERJEE, 2023). The technical literature defines this class of sensors as deeply integrated devices that merge brain-computer interfaces and bioelectronic tissues for sensory or cognitive restoration (MAZZEO, 2025).

Implantable devices require the use of biocompatible materials, nano- and micrometer-scale structures, and architectures that enable wireless communication with external networks, ushering in a new generation of connected biotechnology (Antonelli, 2024). Among the main integrated devices, the following stand out: 1 – Implantable nanochips, defined as nanoscale electronic circuits integrated into neural, muscular, or epithelial tissue, used for reading cellular electrical potentials or for real-time neural modulation; 2 – Molecular biosensors, characterized as devices that interact with specific metabolites, ions, or biomarkers in the intracellular or extracellular environment, consisting of conductive polymers, recombinant DNA, or functionalized graphene; 3 – Bioelectronic materials, which can be defined as synthetic or hybrid fabrics that incorporate flexible circuits sensitive to physiological stimuli, used in electronic skin, implantable pH, pressure, and oxygenation sensors; and 4 - Smart drug delivery systems using micro-reservoirs or nanorobots that release medications in a controlled manner in response to biological signals such as inflammation or changes in pH. These devices have been used therapeutically in the context of various diseases such as: 1 - Precision oncology, in which nanochips are used to detect molecular changes associated with tumors and deliver drugs exclusively to cancer cells, thereby minimizing side effects; 2 - Neuromodulation

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and brain-machine interfaces, where devices integrated into brain structures enable the reading and stimulation of neural circuits, with applications in paralysis, epilepsy, and treatment-resistant depression; 3 - Tissue regeneration using biosensors embedded in scaffolds and subsequently inserted into tissues, which monitor cellular regeneration in real time, optimizing regenerative therapies; and 4 - Early diagnosis of metabolic diseases, where molecular devices detect abnormal levels of glucose, lactate, or other markers, enabling diagnosis before the onset of clinical symptoms.

However, several technological challenges need to be overcome, including: 1 – The need for biocompatible power-harvesting microphones; 2 – Miniaturization and biocompatibility, since the devices must be small enough to operate in biological microenvironments and not cause adverse immune responses; 3 – Durability and functional stability, so that the integrated devices can maintain their function over long periods, withstanding hostile mechanical and chemical environments; and 4 – Development of secure and effective transmission protocols. It is believed that the next generation of integrated devices may present a full technological symbiosis, enabling the redefinition of the concepts of body, health, disease, and identity. Their integration will tend to result in self-adjusting systems, capable of integrating with the microbiome and performing instant therapeutic diagnostics (OBEID, 2024; XI, 2025).

The integration of these sensors poses significant challenges related to the biocompatibility of materials, energy efficiency for prolonged operation, and, crucially, cybersecurity and the integrity of bodily privacy (SANTOS, 2025). The digitization of the biological “self” creates vulnerabilities that transcend traditional boundaries of data protection, requiring new regulatory frameworks that guarantee the individual’s sovereignty over their own biometric information and prevent misuse by third parties (BASSANI, 2021). Thus, the sensors integrated into the IoB are not merely diagnostic tools, but agents of an ontological reconfiguration of human identity in the era of hyperconnectivity, where the body ceases to be an isolated

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entity and becomes a dynamic, programmable, and permanently connected interface within global cyberspace.

4. COMPARATIVE OVERVIEW OF DIFFERENT TYPES OF SENSORS

The evolution of personalized medicine and continuous health monitoring has been significantly driven by advances in biomedical sensing technologies. These technologies are emerging as crucial tools for real-time physiological data collection, early diagnosis, and disease management. Each of these approaches presents a distinct set of advantages and limitations, reflecting different levels of technological maturity and clinical applicability.

Wearable sensors, such as smartwatches and patches, stand out for their non-invasive nature and ease of use, enabling continuous monitoring of parameters such as heart rate and physical activity. Their high technological maturity and widespread commercial availability make them accessible, but they face challenges related to accuracy due to motion artifacts and the stability of skin contact (ATES, 2022). The privacy of the collected data also represents a growing concern. On the other hand, injectable sensors offer a minimally invasive approach, as they can be inserted into deep tissues without the need for complex surgeries. Often based on biocompatible hydrogels, they promise localized monitoring with less external interference. However, their technological maturity is still at an intermediate stage, with many in the research and clinical trial phases, and challenges such as difficulty in removal and limited battery life persist (GU, 2020).

Swallowable sensors provide non-invasive access to the gastrointestinal tract and are valuable for monitoring pH, temperature, and gases, as well as for obtaining internal images, such as with endoscopic capsules. Although they exhibit medium-to-high technological maturity for certain applications, limitations include variable transit time and their single-use nature, which prevents prolonged monitoring at the same site (Lu, 2023). On the other hand, implantable sensors represent the pinnacle of invasiveness, requiring surgical procedures for insertion. However, they

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offer long-term monitoring with high precision due to direct and stable contact with the organ or tissue of interest, making them crucial for conditions requiring constant surveillance, such as in pacemakers and continuous glucose monitoring systems. The risks associated with surgery, infection, and foreign body reaction are their main disadvantages (YOGEV, 2023).

Integrated or bio-integrated sensors, which aim for close integration with biological tissues—such as e-skins—represent the cutting edge of innovation. These devices are designed to have mechanics compatible with soft tissues, enabling multifunctionality that may include sensing and therapy. The technological maturity of integrated sensors is still moderate, with many prototypes in the laboratory and significant challenges in large-scale manufacturing and long-term stability in humid biological environments (SCHEIDT, 2025).

The choice of biomedical sensor type depends critically on the specific application, the acceptable level of invasiveness, the duration of monitoring, and the required accuracy. While wearable and ingestible sensors offer more accessible and less invasive solutions for general health monitoring, injectable, implantable, and integrated sensors promise more accurate and continuous data for complex diagnostics and therapies, albeit with greater engineering and biocompatibility challenges (Table 1). Ongoing research in these areas aims to overcome current limitations and integrate these technologies into a more comprehensive and effective healthcare system.

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Table 1. Comparison of different types of sensors.

SENSOR TYPE	KEY ADVANTAGES	KEY DISADVANTAGES	TECHNOLOGY MATURITY
Wearable	Non-invasive, easy to use, continuous real-time monitoring, relatively low cost.	Accuracy affected by motion artifacts, unstable skin-electrode contact, battery dependency, and data privacy.	High (commercially available: smartwatches, patches).
Injectable	Minimally invasive, they can be placed in deep tissues without complex surgery and offer high biocompatibility.	Difficulty in retrieval/removal, limited battery life (or the need for an external/wireless power source), migration within the tissue.	Low to moderate (many are in the clinical trial phase or at an advanced research stage).
Ingestible	Non-invasive access to the gastrointestinal tract, monitoring of pH, temperature, and gases, and imaging.	Variable transit time, single-pass (passes through the body only once), challenges in achieving precise localization.	Upper-middle (endoscopic capsules are already the gold standard).

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SENSOR TYPE	KEY ADVANTAGES	KEY DISADVANTAGES	TECHNOLOGY MATURITY
Implantable	Long-term monitoring, high precision (direct contact with the organ/tissue), does not require patient cooperation.	Invasive (require surgery), risk of infection, foreign body reaction (fibrosis), difficulty in replacement.	High for specific applications (pacemakers, long-term continuous glucose monitoring), medium for new biosensors.
Integrated	Seamless integration with tissues (e-skin), mechanically compatible (flexible/elastic), multifunctionality (sensing + therapy).	Manufacturing complexity, long-term stability in humid biological environments, integration of rigid electronics into soft substrates.	Medium (many working prototypes in the lab).

5. ANALYSIS OF THE FEASIBILITY AND SCALABILITY OF DIFFERENT TYPES OF SENSORS

The convergence of biotechnology and microelectronics has established a new classification of biological monitoring devices, encompassing wearable, injectable, ingestible, and implantable sensors, as well as integrated systems. However, the transition from the laboratory setting to the clinical and commercial scale requires a rigorous analysis of the technical feasibility and scalability of these technologies.

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Wearable sensors represent the segment with the highest commercial maturity and scalability. Their feasibility is supported by their non-invasive nature and ease of integration into consumer electronics ecosystems. However, scalability for rigorous medical diagnosis faces the “accuracy bottleneck,” where variability in skin-sensor contact and motion artifacts compromise data accuracy, limiting their application in critical clinical conditions (MUKHERJEE, 2022). In contrast, ingestible sensors (smart pills) offer a unique diagnostic window into the gastrointestinal tract. Although technically feasible for pH monitoring and drug delivery, their scalability is limited by high unit costs and safety concerns related to the toxicity of conventional batteries, driving research into biodegradable and galvanic power sources (ABHINAV, 2025).

At the more invasive end of the spectrum, implantable and injectable sensors present unique challenges regarding long-term viability. Implantable sensors, such as those used for continuous glucose monitoring (CGM) or intracranial pressure monitoring, face the “foreign body reaction,” in which fibrous encapsulation degrades the transducer’s sensitivity over time. The scalability of these devices is inherently limited by the need for surgical procedures and specialized medical follow-up. Injectable sensors, on the other hand, operating at the micro- or nanoscale, are emerging as a less invasive alternative for deep tissue monitoring. However, their viability is challenged by the complexity of localization and the need for robust communication protocols through dense human tissues, which exhibit high attenuation of radiofrequency signals (KHALIFA, 2021).

The ultimate frontier lies in the sensors integrated within the IoB paradigm. The viability of these systems depends on the synergistic coordination of different sensory modalities, where data from a wearable sensor can validate the reading from an implantable device, thereby reducing false positives. Scalability, in this context, is not merely physical but informational; the fusion of heterogeneous data streams requires compression algorithms, reduced latency, and robust

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cybersecurity protocols to protect patient privacy and integrity in Medical Internet of Things (IoMT) networks.

In addition to technical challenges, commercial scalability is constrained by regulatory compliance and the standardization of communication protocols, such as Bluetooth Low Energy (BLE) and the Medical Body Area Network (MBAN). Reducing manufacturing costs through the use of specialized semiconductors and large-scale manufacturing processes is essential for these technologies to move beyond niche solutions and reach primary healthcare settings. Ultimately, the transition to ubiquitous monitoring systems requires a digital health infrastructure capable of processing Big Data ethically and efficiently (GHANIM, 2023).

6. REAL-WORLD CASES

The deployment of IoB devices in clinical and consumer settings introduces vulnerabilities that go beyond technical failures, extending to issues of physical safety and biological integrity. Below, we analyze risk scenarios and real-world cases for the five categories of devices.

WEARABLE DEVICES

Although considered low-risk because they are non-invasive, wearable devices have critical vulnerabilities regarding privacy and data integrity. A notable real-world case involved the Strava app, which in 2018 inadvertently revealed the locations of secret military bases through heat maps generated by soldiers' tracking devices. In the clinical setting, the risk lies in relying on inaccurate data for self-medication decisions, where calibration errors in heart rate monitors can lead to anxiety attacks or the unnecessary use of beta-blockers (MUKHERJEE, 2022).

INJECTABLE SENSORS

Injectable sensors, operating at the micro- or nanoscale, face the risk of tissue migration and chronic inflammatory reactions. A significant risk factor is the

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difficulty of removal in the event of electronic failure or material toxicity. Unlike a surgical implant, an injectable sensor can travel through the bloodstream, posing risks of embolism if the encapsulation is compromised. Furthermore, signal attenuation through dense tissues can generate “false negatives” in critical monitoring of tumor biomarkers (KHALIFA, 2021).

INGESTIBLE SENSORS

Smart pills introduce risks related to intestinal obstruction and chemical integrity. Cases of endoscopic capsule retention in patients with Crohn’s disease demonstrate the risk of mechanical complications. From a security standpoint, the risk scenario involves the interception of radio signals emitted by the capsule during gastrointestinal transit, which could expose data on the patient’s medication adherence to unauthorized third parties (ABHINAV, 2025).

IMPLANTABLE SENSORS

This category poses the most severe cybersecurity risks. In 2017, the FDA issued a recall alert for nearly 500,000 St. Jude Medical pacemakers due to vulnerabilities that allowed hackers to alter the device’s programming or drain the battery remotely. The risk scenario here is “digital murder,” where control of an implantable cardioverter-defibrillator (ICD) is hijacked to deliver fatal shocks or cease cardiac stimulation (HASSIJA, 2021).

INTEGRATED SENSORS

The risk in integrated systems (closed-loop IoB) lies in data fusion failure. A critical scenario occurs in integrated artificial pancreases, where a hacked or defective wearable glucose sensor sends false data to an implanted insulin pump. If the decision algorithm lacks cross-verification mechanisms, the erroneous administration of massive doses of insulin can induce a fatal hypoglycemic coma. The complexity of the integrated sensor network expands the attack surface, where

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a single less-secure component can serve as a gateway to compromise the user's entire biological ecosystem (GHANIM, 2023).

7. THE INTELLIGENCE OF BODIES: SYNERGY BETWEEN SENSORS AND THE INTERNET OF BODIES

AIoB represents a paradigm shift in digital health, where the human body ceases to be a passive object of observation and becomes an active, intelligent node in a connected network known as IoB (CELIK, 2022). This intelligence is not limited to simple data collection but involves local processing (edge computing) and predictive analysis through artificial intelligence (AI), enabling real-time interventions. The operation of this intelligence varies depending on the technological interface used: wearable, injectable, ingestible, implantable, and integrated sensors.

In wearable sensors, body intelligence operates on the external layer, monitoring physiological parameters such as heart rate, oxygen saturation, and movement patterns (AL-KAHTANI, 2022). Here, AIoB manifests itself in the ability to filter out ambient noise and identify behavioral patterns, such as detecting falls in the elderly or the onset of anxiety attacks, providing immediate feedback to the user and healthcare professionals.

Injectable sensors take this interaction to the tissue level. Often based on hydrogels or nanotechnology, these devices are injected into the subcutaneous tissue to continuously monitor chemical biomarkers, such as glucose or lactate, over long periods (MAZZEO, 2025). The AIoB, in this case, lies in the translation of complex biochemical signals into precise digital data, enabling metabolic monitoring without the need for bulky external devices.

In the gastrointestinal tract, ingestible sensors (smart pills) act as mobile laboratories. Equipped with cameras, pH sensors, or gas detectors, these devices travel through the digestive system collecting data on the microbiota and mucosal integrity (KALANTAR-ZADEH, 2017). AIoB coordinates the transmission of this data

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through human tissues (body-conduction communication) to external receivers, enabling non-invasive diagnosis of inflammatory diseases or malabsorption.

Implantable sensors represent the most advanced form of integration, as they are surgically inserted to replace or assist with bodily functions, such as smart pacemakers and brain-computer interfaces (YOGEV, 2023). AIoB operates here in closed-loop systems, where the sensor not only detects an arrhythmia or an anomalous neural pattern but also triggers an immediate therapeutic response, such as an electrical pulse, acting autonomously to maintain homeostasis.

Integrated sensors consolidate all these fronts into a holistic ecosystem. Through Body Area Networks (BANs), different sensors communicate with one another, allowing a cardiac implant to adjust its function based on physical activity data from a wearable or the metabolic state of an injectable (CELIK, 2022). This intelligent orchestration creates a “digital twin” of the patient, enabling simulations and highly personalized treatments.

AIoB, mediated by this diversity of sensors, is transforming reactive medicine into a proactive and personalized practice. Although the benefits are vast, continued evolution requires robust solutions to challenges related to biosafety, data privacy, and long-term biocompatibility.

8. CONCEPTUAL MODEL OF THE IoB-AIoB ECOSYSTEM

The evolution from IoB to AIoB marks a paradigm shift: from passive monitoring systems to ecosystems of proactive and autonomous intervention. The conceptual model of an IoB-AIoB ecosystem is structured as a symbiotic architecture that integrates biosensors, edge computing, and deep learning algorithms to create a ubiquitous “layer of embodied intelligence.”

The IoB-AIoB ecosystem can be understood through a four-layer architecture: Perception, Transmission, Intelligence, and Action. In the perception layer, heterogeneous sensors (wearable, implantable, and injectable) collect multidimensional streams of physiological and behavioral data. The transition to

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AIoB occurs in the intelligence layer, where Artificial Intelligence of Things (AIoT) models perform real-time data fusion. Unlike traditional IoT models, AIoB requires a "design intelligence" that considers the systemic dynamics of the human body, treating it not merely as a data source but as a complex and adaptive biological environment (PHATAK, 2021; MARTÍNEZ RUIZ, 2025).

The transmission layer uses wireless body area networks (WBANs) and low-latency protocols to ensure that the decision pipeline does not experience critical delays. The major innovation of the AIoB ecosystem lies in the action layer, where the system closes the loop by translating algorithmic insights into physical interventions. This conceptual model replaces fragmented human decision-making with automated and continuous orchestration (MOUSTATI, 2024).

The synergy between IoB and AIoB is underpinned by the ability to transform raw physiological markers into subjective and predictive states. The AIoB ecosystem uses neural networks to identify subtle patterns that precede clinical events, such as an arrhythmia or a seizure, enabling precision preventive medicine. However, integration requires formal adaptation models that ensure the system's resilience in the face of biological variations and sensor noise (ZHOU, 2025).

Furthermore, the AIoB conceptual model must incorporate "practical governance" to ensure user trust. The complexity of the ecosystem, which involves multiple manufacturers and flows of sensitive data, requires robust standards for semantic interoperability and cybersecurity. Ultimately, the IoB-AIoB ecosystem represents the definitive fusion between the biological and the digital, where artificial intelligence ceases to be an external tool and becomes a functional extension of the body itself (CHEN, 2024; MARTÍNEZ RUIZ, 2025).

9. CONCEPTUAL MODELS AND ALGORITHMIC LIMITATIONS IN THE INTERNET OF BODIES

The IoB represents an evolution of the IoT, in which the human body acts as the primary source of data through connected devices. For this technology to be

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effective and secure, it is essential to establish robust conceptual models that describe data flows and decision pipelines. At the same time, it would face critical algorithmic limitations, such as bias, interpretability, and data dependency.

Conceptual models in IoB are structured as a multi-layered architecture, often described as an ecosystem that integrates biological and behavioral sensors. The data flow begins at the body perception layer, where sensors (wearable, implantable, or injectable) capture physiological signals, such as heart rate, glucose levels, or sleep patterns. This raw data is transmitted via body area network (BAN) protocols to an edge layer, such as a smartphone, which performs preprocessing and initial filtering (MARINESCU, 2025).

The subsequent decision pipeline involves ingesting this data into cloud platforms, where machine learning (ML) algorithms perform predictive analysis and pattern detection. This pipeline is cyclical and dynamic, operating in a closed-loop: the processed data generates insights that can feed back into the device for immediate action, such as the automatic adjustment of insulin delivery in smart pumps, or inform complex clinical decisions by healthcare professionals. The efficiency of this model depends on semantic interoperability across different manufacturers and the ability to process heterogeneous data streams in real time, ensuring that the decision cycle is continuous, resilient, and accurate (LIU, 2026).

In this context, the decision pipeline is not limited to diagnosis but extends to proactive intervention. The architecture must include mechanisms for redundancy and data fusion from multiple sensors to reduce uncertainty and increase the statistical confidence of the automated decision. The transition to a “behavioral influence” model (Internet of Behaviors—IoB) adds complexity, as the system seeks not only to monitor but also to induce positive changes in the user’s lifestyle through personalized digital interventions (ZHAO, 2023).

Despite its transformative potential, body intelligence faces significant barriers related to the nature of the algorithms used. Data dependency is the primary limitation; IoB algorithms require vast, continuous, and high-quality datasets

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for training. The lack of standardization in biological data collection can lead to models that fail in real-world scenarios, where physiological “noise” is common. Furthermore, excessive reliance on historical data can prevent the system from identifying unprecedented or rare anomalies (CELIK, 2021).

Algorithmic bias has emerged as a central ethical and technical concern. If training data is not representative of human diversity (in terms of ethnicity, gender, age, or socioeconomic status), the resulting models may exhibit performance disparities. For example, pulse oximetry sensors have demonstrated lower accuracy on darker skin tones, a bias that, if replicated in automated decision pipelines, can lead to misdiagnoses and systemic health inequities (NADERALVOJOUD, 2025).

Interpretability (or the lack thereof) is another critical barrier that directly impacts the trust of users and healthcare professionals. Many deep learning models operate as “black boxes,” where the internal logic leading to an automated clinical decision—such as the identification of an arrhythmia—is not easily auditable or comprehensible. In critical IoB applications, where decisions can have direct consequences on an individual’s physical well-being, algorithmic transparency becomes an indispensable ethical and legal requirement. The emergence of Explainable Artificial Intelligence (XAI) seeks to mitigate this problem through techniques such as relevance heatmaps or local surrogate models, providing understandable justifications for the generated predictions (VAN DER VELDEN, 2022).

The lack of interpretability also makes it difficult to identify logical errors or spurious causality, where the model may base decisions on accidental correlations rather than actual biological markers. For the large-scale adoption of IoB, developers must balance the complexity and accuracy of models with the need to provide clear explanations regarding the basis for each recommendation, ensuring that human judgment remains the final authority (MOUSTATI, 2025).

The consolidation of IoB requires that conceptual models evolve beyond simple connectivity, incorporating mechanisms that mitigate biases and increase

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transparency. The scalability of body intelligence will depend on our ability to create systems that not only collect data but do so in an ethical, interpretable, and resilient manner, accounting for the inherent variations in human biology (MARINESCU, 2025; NADERALVOJOUD, 2025).

10. REGULATORY FRAMEWORKS AND GOVERNANCE IN THE INTERNET OF BODIES

The rapid expansion of the IoB poses unprecedented challenges to global legal systems, requiring the adaptation of regulatory frameworks to address the intimate and continuous nature of the data collected. Regulations such as the European Union's General Data Protection Regulation (GDPR) and Brazil's General Data Protection Law (LGPD) are emerging as fundamental pillars for ensuring users' privacy, security, and autonomy in digital health ecosystems and connected devices.

Both the GDPR and the LGPD are grounded in principles of transparency, purpose, and necessity. In the context of the IoB, the classification of physiological and behavioral data as "sensitive data" requires a high level of protection. The GDPR, in Article 9, prohibits the processing of health-related data, except under specific conditions, such as explicit consent or public interest in health (FERETZAKIS, 2025). The LGPD follows a similar logic, establishing strict legal frameworks for the processing of biometric and genetic data, which are essential for mitigating risks of algorithmic discrimination and leaks of critical information (VILELA, 2026).

However, the implementation of these frameworks faces the "challenge of ubiquity." IoB devices often operate in the background, making it difficult to obtain truly free and informed consent. Furthermore, data portability—a right guaranteed by both laws—becomes technically complex due to the lack of semantic interoperability among sensor manufacturers. Regulatory compliance therefore requires the implementation of Privacy by Design and Privacy by Default strategies,

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integrating data protection from the hardware and software design phase (CORDEIRO, 2024).

The effectiveness of regulatory frameworks in the Internet of Things (IoT) depends on the ability of supervisory authorities (such as the ANPD in Brazil) to monitor cross-border data flows and audit automated decision-making algorithms. International harmonization of standards is essential to prevent “data havens” and ensure that technological innovation does not occur at the expense of fundamental personality rights (ABHINAV, 2025).

IoB governance requires coordination between general data protection laws and sector-specific regulations. While the GDPR (European Union) and the LGPD (Brazil) establish cross-cutting privacy principles, other international frameworks, such as HIPAA (U.S.), the EU AI Act, and Asian laws like the PIPL (China), offer distinct approaches to the management of biometric data and algorithmic risk.

The main distinction between the Euro-Brazilian model and the U.S. model lies in their scope of application. The GDPR and the LGPD adopt an omnibus approach, regulating any processing of personal data, regardless of the sector. In contrast, HIPAA (Health Insurance Portability and Accountability Act) is sector-specific, applying only to “covered entities” (hospitals, insurers) and their business partners (SHARMA, 2025).

For the IoB, this difference is critical: data collected by a consumer smartwatch in the U.S. may not be protected by HIPAA if it is not integrated into an official medical record, whereas in the EU and Brazil, that same data is classified as sensitive and protected from the moment of initial collection. However, HIPAA imposes more prescriptive technical security standards (Security Rule) for the storage of electronic health information than the principles-based nature of the GDPR (ONETRUST, 2024).

Europe has advanced in regulating IoB with the EU AI Act, which introduces a risk-based classification for artificial intelligence systems. Many IoB devices, especially implantable ones that perform automated diagnostics, may be classified

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as “high-risk,” requiring rigorous audits and algorithmic transparency prior to commercialization (FERETZAKIS, 2025). This is an additional layer that the LGPD does not yet have in such a structured form, although Brazil is discussing Bill 2338/2023 to fill this gap.

In Asia, China’s PIPL (Personal Information Protection Law) is comparable to the GDPR in terms of strictness, but places greater emphasis on data sovereignty and national security. The PIPL requires that biometric data collected on a large scale be processed locally, which impacts the global scalability of implantable sensor companies. Japan, on the other hand, with the APPI (Act on the Protection of Personal Information), focuses on facilitating the flow of data for medical research, offering a balance between protection and innovation that has served as a model for the integration of wearable technologies into public health systems (VILELA, 2026).

Therefore, while the GDPR and LGPD offer the most comprehensive protection for individuals, HIPAA focuses on the integrity of the healthcare system and the EU AI Act on the security of the technological device. For the IoB, compliance requires navigating this regulatory patchwork, where data protection (privacy) must coexist with device security (cybersecurity) and algorithmic ethics (SHARMA, 2025; FERETZAKIS, 2025).

11. BIOETHICS, TECHNOPOLITICS, AND THE SOCIOECONOMIC DIMENSIONS OF THE INTERNET OF BODIES

The consolidation of the IoB goes beyond biomedical innovation, establishing itself as a technopolitical phenomenon that reshapes the relationship between the human body, the state, and capital. The transition from biological bodies to “datafied bodies” requires a critical analysis that integrates the principles of traditional bioethics with the new power dynamics and structural inequalities exacerbated by technology.

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The IoB acts as a vector of biopower, a Foucauldian concept that describes the control of bodies and the regulation of populations through surveillance technologies. From a technopolitical perspective, the continuous collection of biometric data by wearable and implantable sensors is not neutral; it serves security and productivity agendas that can marginalize historically vulnerable subjectivities. The "technopolitics of surveillance" manifests itself in the ability to monitor not only health but also behavior and emotions, transforming biological intimacy into an economic asset and a tool of social control (MÜLLER, 2023).

The risk lies in the normalization of omnipresent surveillance under the guise of care, where the body becomes a node in a network of algorithmic governance. This governance can be exercised invisibly, through digital "nudges" that seek to shape individual behavior in accordance with predefined health and productivity standards. The technopolitics of the IoB, therefore, redefines individual sovereignty, transferring part of the authority over one's own body to automated systems and data infrastructure owners (MATWYSYHN, 2019; SILVA, 2021).

The socioeconomic implications of the IoB are marked by the risk of a new form of stratification: "biological inequality." The high cost of implantable and integrated sensors can create a chasm between those who can afford cognitive and physiological enhancements and those who remain limited by natural biology. This scenario of "transhumanism for the few" threatens to crystallize economic disparities into permanent biological differences, in which access to predictive health care and optimized performance becomes a class privilege. The disparity lies not only in access but in the very definition of "normality," where those without the technology may be viewed as "suboptimal" or less productive (SHARMA, 2025).

Economically, IoB fuels surveillance capitalism, in which raw biological data is refined into behavioral prediction products. Health insurers and employers can use data streams from wearable sensors to penalize individuals with genetic predispositions or lifestyle habits deemed "suboptimal," exacerbating job insecurity and social exclusion. This dynamic can lead to "data poverty," in which individuals in

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vulnerable situations are forced to trade their biological privacy for access to basic services or jobs. Furthermore, reliance on proprietary platforms for the operation of vital devices creates a new form of economic vulnerability, in which the closure of a company or a change in terms of service can leave users literally “disconnected” from their vital functions. In short, the viability of the IoB as a tool for human progress depends on ethical governance that prioritizes social justice and the protection of human dignity in the face of the commodification of the body (ZHAO, 2023).

In the field of bioethics, IoB challenges the pillars of autonomy and beneficence. The integration of sensors into the human body raises fundamental questions about the integrity of personal identity. Devices such as brain-computer interfaces (BCI) or neural implants can alter an individual’s perception of agency, creating a hybrid “self” whose will is mediated by algorithms. Informed consent becomes problematic when data processing is opaque and the long-term consequences of technological integration are unknown. Furthermore, the transhumanist imperative of bodily “enhancement” can generate coercive social pressures when refusal of technological integration results in exclusion or competitive disadvantage (WILKINS, 2025; ABHINAV, 2025).

The transition from IoB to AIoB introduces a layer of algorithmic autonomy that challenges the foundations of bioethics and civil law. Unlike passive monitoring devices, closed-loop AIoB systems have the ability to make executive decisions regarding the user’s biological state without direct human intervention, which requires a reassessment of current regulatory frameworks.

The main ethical challenge of AIoB lies in the tension between the system’s autonomy and the individual’s personal autonomy. In devices such as artificial pancreases or closed-loop brain-computer interfaces (BCIs), the algorithm can make physiological adjustments (such as The integration of neural sensors into the AIoB ecosystem raises the challenge of mental privacy. Unlike heart rate data, neural signals can reveal underlying cognitive states, intentions, and emotions. The

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risk of corporate or state “neuro-surveillance” calls for the creation of new fundamental rights—so-called “neuro-rights”—that protect cognitive freedom and the privacy of brain data against commercial exploitation. Regulation of AIoB must therefore transcend hardware and software security, incorporating principles of neuroethics that ensure artificial intelligence acts as a support for human dignity, and not as a tool for the technological colonization of the biological self (RUIZ-VANOYE, 2024).

The release of drugs or neural stimuli) based on statistical predictions. This scenario raises the question of “delegated agency”: to what extent does the user retain control over their own body when their vital functions are mediated by proprietary artificial intelligence? The opacity of deep learning models (the black-box problem) exacerbates this dilemma, as the user may not understand the logic behind a bodily intervention, compromising the principle of ongoing informed consent (KELLMEYER, 2016)

From a regulatory standpoint, AIoB creates a legal liability vacuum. In the traditional model, liability for a medical error or device failure is shared among the manufacturer, the physician, and the hospital. However, in highly autonomous AIoB systems, identifying the causal link to an adverse event becomes complex. If an AI algorithm makes an erroneous decision based on biased training data or an incorrect interpretation of noisy signals, who should be held accountable?

Current regulatory frameworks, such as the GDPR and the LGPD, focus on data protection but are insufficient to address the physical harm resulting from an autonomous algorithmic decision. The EU AI Act seeks to mitigate this by classifying AI-based healthcare systems as high-risk, requiring safety audits and “human-in-the-loop” mechanisms. However, the effectiveness of these mechanisms is limited by the speed of biological reactions, which may make human intervention too late to prevent anaphylactic shock or a system-induced seizure (MENNELLA, 2024; MOHAMMED, 2025).

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The integration of neural sensors into the AIoB ecosystem raises the challenge of mental privacy. Unlike heart rate data, neural signals can reveal underlying cognitive states, intentions, and emotions. The risk of corporate or state "neuro-surveillance" calls for the creation of new fundamental rights—so-called "neuro-rights"—that protect cognitive freedom and the privacy of brain data against commercial exploitation. Regulation of AIoB must therefore transcend hardware and software security, incorporating principles of neuroethics that ensure artificial intelligence acts as a support for human dignity, and not as a tool for the technological colonization of the biological self (RUIZ-VANOYE, 2024).

12. BIOMETRIC DATA SOVEREIGNTY AND NEURO-RIGHTS

The convergence of the Internet of Brain (IoB) and advanced neurotechnologies calls for the development of new legal and ethical paradigms that go beyond conventional data protection. The concepts of biometric data sovereignty and neurorights emerge as responses to the growing capacity of automated systems to monitor, decode, and potentially modulate an individual's physical and mental states (CIRILLO, 2025).

Biometric data sovereignty proposes that the individual must retain ultimate and exclusive control over the information generated by their own body. In the context of the IoB, where sensors capture continuous streams of physiological data (heart rate, hormone levels, sleep patterns), sovereignty goes beyond simple consent. It implies the right to "bodily informational self-determination," ensuring that the user can decide not only who accesses their data, but also how it is interpreted and used in decision-making pipelines (BODDINGTON, 2023).

The lack of sovereignty creates the risk of "data colonialism," where companies that own IoB infrastructure extract value from biological privacy without ethical accountability or transparency. The implementation of sovereign digital identities and citizen data enclaves emerges as a technical solution to restore users'

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authority over their “digitized selves,” ensuring that innovation in digital health does not result in the expropriation of biological privacy (IENCA, 2021).

Advances in brain-computer interfaces (BCIs) and neural sensors integrated into the IoB have sparked a debate on neuro-rights. These are defined as ethical and legal principles designed to protect a person’s cerebral and mental domain against unauthorized intrusions or algorithmic manipulations. The framework of neurorights is structured around five fundamental pillars: mental privacy, cognitive freedom, personal identity, free will, and equitable access to neurotechnological enhancement (GUERRERO, 2024).

Mental privacy is the most critical of these boundaries, as it seeks to prevent neural data—which can reveal underlying thoughts, intentions, and emotions—from being collected or analyzed without strict safeguards. Cognitive freedom, in turn, protects an individual’s right to maintain control over their own mental processes, resisting attempts at external modulation via neurostimulation or algorithmic “nudges.” Countries such as Chile, pioneers in including neuro-rights in their constitutions, have recognized that the integrity of the mind is the foundation of human dignity in the age of artificial intelligence (BROWN, 2024).

The consolidation of the IoB depends on the institutionalization of biometric sovereignty and neuro-rights. These frameworks ensure that the body and mind remain spaces of inalienable autonomy, preventing total connectivity from becoming a tool of absolute biopolitical surveillance (GUERRERO, 2024).

13. FINAL CONSIDERATIONS

IoB represents a paradigm shift in the evolution of the IoT, extending digital connectivity directly to the human domain through a wide range of devices. This emerging technology integrates the human body into digital networks, enabling the collection, transmission, and analysis of physiological and behavioral data in real time.

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The potential benefits of IoB are vast and transformative, especially in the health and wellness sectors. The ability to continuously and non-invasively monitor vital signs could revolutionize disease prevention, early diagnosis, and the management of chronic conditions, significantly improving patients' quality of life. Beyond healthcare, IoB can optimize athletic performance, workplace safety, and even human interaction with digital environments. However, the widespread implementation of IoB is not without complex and multifaceted challenges. Data privacy concerns are paramount, given the highly sensitive nature of the biometric and health information collected. Cybersecurity emerges as a critical pillar, as the vulnerability of IoB devices to attacks can have catastrophic consequences for individuals' safety and lives. Ethical and governance issues are also prominent, ranging from informed consent and individual autonomy to the risk of discrimination and algorithmic bias.

AIoB, driven by the convergence of advanced sensing technologies, represents a major milestone in personalized medicine and digital health. The ability to collect and interpret physiological and behavioral data in real time, through wearable, injectable, ingestible, implantable, and integrated sensors, not only enhances monitoring and diagnosis but also enables proactive and adaptive therapeutic interventions. Although the potential to transform quality of life and longevity is immense, the full realization of IoB requires overcoming critical challenges related to cybersecurity, data privacy, ethics in the handling of biological information, and ensuring long-term biocompatibility. The future of healthcare therefore lies in continuous innovation and multidisciplinary collaboration to build smart healthcare ecosystems that are effective, safe, and equitable.

IoB represents a technological frontier with the potential to redefine the interaction between humans and the digital world. For its full potential to be realized in a responsible and beneficial manner, it is imperative that technological advances be accompanied by a robust regulatory, ethical, and safety framework. Collaboration among researchers, policymakers, industry, and civil society will be

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crucial to addressing the inherent challenges and ensuring that IoB serves human well-being, protecting individual dignity and rights in an increasingly connected future.

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