Review

BASOSH – A Conceptual Framework and Literature Review on Body-Centric Antenna Systems for Occupational Safety and Health

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BASOSH — A Conceptual Framework and Literature Review on Body-Centric Antenna Systems for Occupational Safety and Health

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Abstract

Occupational Safety and Health (OSH) is increasingly relying on wearable technologies, yet research on such body-centric antenna systems remains fragmented across diverse disciplines. This review introduces and formalizes the concept of Body-Centric Antenna Systems for Occupational Safety and Health (BASOSH), defined as integrated systems where electromagnetic performance, human-body interaction, and OSH goals are intrinsically coupled. Based on a preliminary scientometric analysis, the existing literature is categorized into four applicative pillars: *i*) monitoring workers' health and safety, *ii*) supporting occupational activity, *iii*) preventing accidents and mitigating risks, and *iv*) rehabilitation and prosthetics. The review highlights a lack of integrated design approaches, with a few reports converging towards a unitary analysis that has not been formalized before. Hence, this work establishes BASOSH as a unitary framework for these systems and a distinct research domain, with recurring challenges such as performance conflicts and the need for system-level design. A functional weighting wireless parameters, human body presence, and OSH consequences is lastly proposed to design and compare different systems. By systemizing a sparse research field, BASOSH aims to foster personalized safety solutions and improve working conditions worldwide.

Keywords: Antenna systems; BASOSH; bodycentric Internet of Things; epidermal antennas; industrial safety; occupational safety and health; wearable antennas

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1. Introduction

Occupational Safety and Health (OSH) is commonly defined as the science concerned with anticipating, recognizing, evaluating, and controlling hazards that arise in or from the workplace that may affect the health and well-being of workers, while also considering the broader impact on surrounding communities and the environment [1]. By its very nature, OSH is a highly interdisciplinary domain that encompasses engineering, medicine, ergonomics, environmental science, sociology, and even rehabilitation, including prosthetics and full recovery of injured workers. Its conceptual roots can be traced back to the XVII century, with French Manufacturer Inspectors [2], and to the XVIII century, with the pioneering work of Bernardino Ramazzini, widely regarded as the founder of occupational medicine [3]. In modern times, occupational health and occupational safety have progressively converged into a unified discipline, now broadly referred to as OSH, as formalized by global institutions such as the International Labour Organization (ILO) [1,4].

In parallel with this evolution, recent technological advances have reshaped the way workplace risks are monitored and mitigated. Among these, body-centric (or bodycentric) antenna systems have recently emerged as a key enabling technology for continuous and context-aware sensing on the human body. Technological enablers of body-centric wireless communications [5,6], these systems are designed to operate in close proximity to, on, or even within the human body, accounting for its complex electromagnetic properties. Their integration with wearable and epidermal electronics has further expanded their applicability, allowing lightweight conformal devices to seamlessly interface with the human body [7]. It is interesting to note that OSH applications were envisioned as soon as bodycentric electromagnetism was systematized [8], foreseeing the intrinsic connection between the physical layer and the actual uses in this work analyzed.

In recent years, the paradigm of the bodycentric Internet of Things (B-IoT) has also been developed to describe interconnected ecosystems of body-worn and body-embedded devices capable of processing and communicating physiological and environmental data in real time [9,10]. This paradigm aligns naturally with the increasing demand for personalized and adaptive approaches to OSH, where monitoring solutions must account for individual variability in exposure, physiology, characteristics, and behavior. In this context, a growing body of literature has explored the application of body-centric antennas to occupational environments, demonstrating their potential to monitor hazardous exposures, enabling finer worker localization and management, and supporting assistive and rehabilitative technologies [11,12]. However, these contributions remain fragmented across disciplines (antenna design, telecommunication systems, medical reports...), overall still lacking a unifying conceptual framework, and rarely considering the cross-domain challenges. This fragmentation reveals a fundamental constraint: *in these systems, electromagnetic performance, human-body interaction, and OSH requirements are inherently coupled and cannot be independently designed or optimized*. This coupling defines a core research problem for the field and requires integration by a unitary framework.

In order to address this gap in scientific knowledge, the present review introduces and formalizes the concept of Body-Centric Antenna Systems for Occupational Safety and Health (BASOSH), building upon prior foundational work that preliminarily presented the idea to the academic community [13]. BASOSH are here formalized as integrated systems that leverage body-centric antennas as core components for sensing and/or communicating in occupational contexts. By linking advances in electromagnetics, wearable technologies, and OSH practices, BASOSH aims to provide a coherent research direction for the next-generation of human-centered safety systems. The objective of this review is therefore twofold: first, to consolidate the existing knowledge spanning body-centric antennas, wearable electronics, and OSH applications; and second, to establish BASOSH as a distinct and strategically relevant research domain, outlining its unique key challenge. In the following pages, accordingly, the BASOSH framework is introduced and used to critically survey the existing literature and, in the end, opportunities and open issues are discussed, whilst proposing a holistic approach to design and evaluation through a high-level functional.

2. BASOSH: Definition and Applications

Based on the sparse literature we analyzed (see the Appendix for technical details on the literature survey), a BASOSH is a specific kind of antenna system wherein the EM (electromagnetic) performances are intrinsically related to workers and their vocational activities. The application to work-related environments or occupations is essential to both distinguish a BASOSH from a generic medical AS (antenna system) and optimize the system's functioning in highly challenging and specific boundary conditions typical of the work domain such as harsh environments, difficult operations, time constraints, and impact on the worker's health. BASOSH can therefore be formalized as the simultaneous presence of three essential components: *i*) a physical layer involving antennas, *ii*) the presence of the human body intrinsically coupled with electromagnetic fields, and *iii*) an OSH application or issue to be addressed (Fig. 1). Consequently, the design space of such systems is jointly constrained by electromagnetic performance, human-body interaction, and OSH requirements, with non-separable coupling among these dimensions.

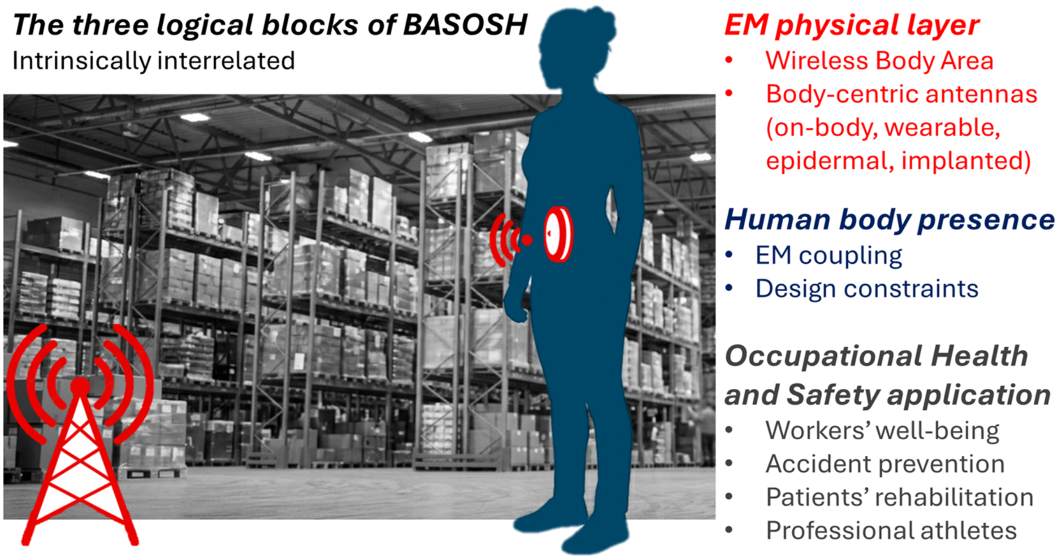


Figure 1. Components constituting a BASOSH.

From the preliminary analysis of the literature, the reports are divided into four applicative pillars: *i*) monitoring the health and safety of workers, *ii*) supporting occupational activity, *iii*) preventing known accidents and mitigating risks, and *iv*) rehabilitation and prosthetics. Since BASOSH is an emerging research domain, the majority of reports do not focus on the relationships between the three constituting blocks; especially, the work application is sometimes implied, mentioned, or given as the overarching goal justifying the research work. The medical, sportive and rehabilitation fields, in particular, just partially overlap with vocational applications. However, since professional athletes and task-focused rehabilitation are intrinsically related to the OSH domain, a few selected reports are included in the following survey of the literature based on the expected impact for the OSH research community. The bibliographic tables Table 1 and Table 2 organize the existing literature, while Fig. 2 depicts all the BASOSH application fields and their categorization, providing a taxonomy of the wide field of research. As is evident in the following, BASOSH spans across multiple disciplines (electromagnetism, telecommunications, occupational medicine, industrial safety, etc.) and is a recognizable, emerging domain, with a delimited focus and recurring issues that are currently addressed by borrowing techniques from other research areas. In the literature, no contribution simultaneously addresses all three BASOSH dimensions in a formalized way; at the beginning of each survey section, therefore, we use the BASOSH framework to investigate which components of the triad (EM performance, body interaction, OSH goals) are explicitly addressed or left implicit by existing works.

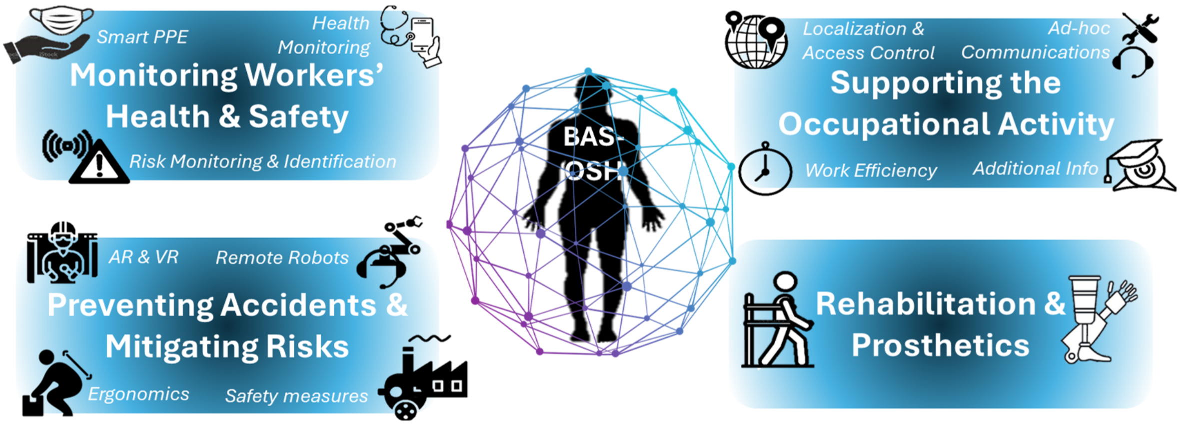


Figure 2. Taxonomy of the BASOSH applications present in the scientific literature.

Table 1. Bibliographic table on telemonitoring workers and supporting their activities.

Class of Application	Application	Details	References
Monitoring Workers' Health and Safety	Enhancing PPE	Workers' status	[14–19]
		Correct usage	[20–22]
		Hazards detection	[23,24]
		PPE integrity	[25]
		Life cycle data	[26]
	(Tele)Monitoring worker	Common workplaces	[27–31]
		Harsh environments	[32–34]
		Sweat monitoring	[35–37]
		Chronic illness	[38]
	Risk monitoring and identification	On-body sensors	[39–41]
		Context-aware systems	[42–45]
		Near-miss detection	[46,47]
Supporting the Occupational Activity	Localization and access control	Localization	[48–52]
		Risk assessment	[53–55]
	Ad-hoc communications	Work-optimized links	[56–59]
		Disaster management	[60–63]
		In-clothes antennas	[64–67]
		Body-UAV links	[68–70]
	Work efficiency	Working cobots	[71–75]
		Working robots	[75,76]
		Workers' well-being	[77,78]
	Additional environmental info.	Hazards monitoring	[79–81]
		Sensorial ultrability	[82–84]

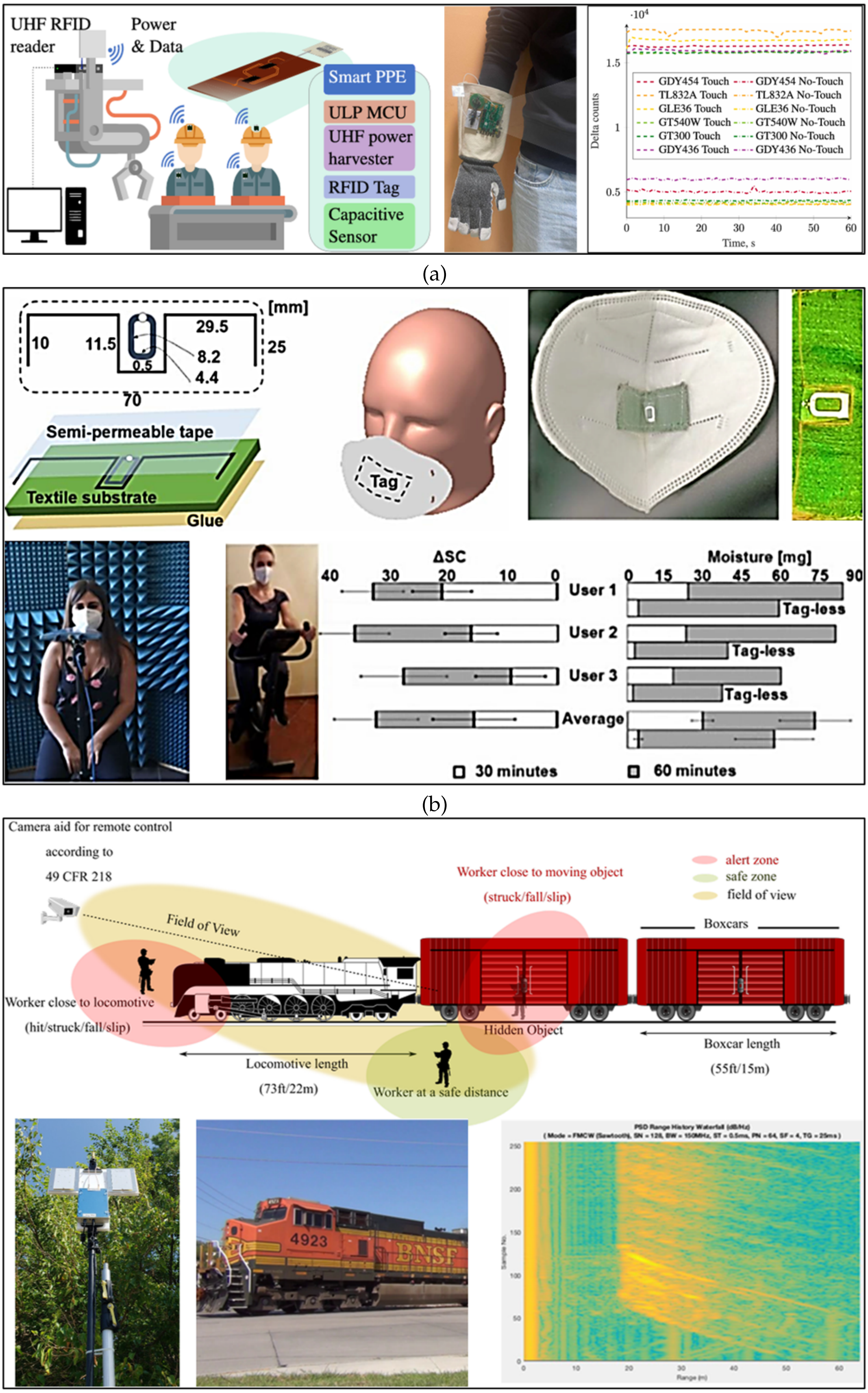
3. Monitoring Workers' Health and Safety

The first applicative domain concerns monitoring the worker's health and safety by exploiting wireless sensors (Table 1). It is the most straightforward and developed use of BASOSH, and many prototypes were manufactured and tested. As it is evident in the remainder of this Section, none of the works in this applicative pillar quantifies the OSH benefit when designing the system, leading to just a partial integration according to the BASOSH framework.

3.1. Enhancing Personal Protective Equipment

PPE (personal protective equipment) is fundamental to preserving OSH, and pervasive sensing technology can provide it with smart capabilities such as checking worker health and posture, detecting hazards, or examining the integrity and functionality of the PPE itself. Organizational measures regarding the correct usage of PPE without enabling sensing are also crucial and they are discussed next in Sec. 5.4.

UHF (ultra-high frequency) RFID (radiofrequency identification) technology exploits radiowave backscattering and is therefore extremely effective for low-cost and low-maintenance sensorization. Such sensors can, for example, detect touch if integrated into protective gloves [20] (Fig. 3(a)) and/or monitor whether the PPE itself is still functioning correctly based on its current status [25] (Fig. 3(b)) or even its life cycle data [26]. The correct use of PPE can be monitored by integrated sensors [21,22], and external environmental hazards can be monitored by the PPE itself, which can communicate with an oversight center owing to protocols such as LoRa [23]. Wearable and textile antennas, eventually combined with long-range protocols, are the main enablers of this critical application.



(a)

(b)

(c)

Figure 3. Examples of BAS monitoring workers' OSH. (a) Protective gloves with capacitive sensor for touch detection (adapted from [20]). (b) Sensorized facemask for moisture detection, showing when it should be replaced due to excessive humidity through the digitalized metric ΔSC (differential sensor code; adapted from [25]). (c) Radar system for automated detection of near-misses, tested in the proximity to a railroad (adapted from [46]).

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3.2. (Tele)Monitoring Workers' Health

For monitoring the workers' health, wireless body-worn sensors for multiple measurands (such as biomarkers, heart rate variability, body temperature, etc.) and/or external factors (noxious substances like toxins and nanomaterials, environmental factors like noise, microclimate, radiation, vibrations, etc.) can be used. In common workplaces like industries or constructions, meters and devices are naturally different from the specialized ones in harsh environments, which come with unique sets of goals and risk considerations.

In ordinary occupational environments, such as offices, control rooms, and lean manufacturing workplaces, the primary objective of telemonitoring is not immediate hazard detection, but rather the long term assessment of physiological well being, fatigue, cognitive load, and comfort. For example, Bluetooth Low Energy (BLE) devices can integrate photoplethysmography, skin temperature sensors, and inertial measurement units (IMUs) to remotely assess heart rate, oxygen saturation, posture, and motion levels during daily work activities [27]. Wireless electroencephalography (EEG) can directly measure workers' attention and/or mental workload, for vigilance monitoring or procedures development [29]. A representative example of a design for harsh working environments is given by Heurtefeux *et al.* in [33]: a Zigbee-Wi-Fi platform is designed to continuously capture inertial and EEG data using low power communication protocols and adaptive data reduction mechanisms. Indeed, in harsh environments, minimizing the contention of radio channels and energy consumption becomes critical, as the reliability of communications directly impacts the timeliness of anomaly detection. However, the study falls short of linking service outages with risk increases.

Sweat monitoring sensors deserve special mention because of their recent significant advancements and multiple OSH applications [35]. Beyond the psychophysical state of workers, they can also monitor sport activity with benefits for both professional athletes and rehabilitative sport-therapy [36]. Epidermal antennas are the preferred technology for this application given that they do not hinder body movement. Lastly, wireless medical devices are also being studied in workplaces to control chronic conditions such as epilepsy, which can pose major OSH challenges [38].

3.3. Risk Monitoring and Identification

The real-time data transmission directly from the worker's WBAN can allow the identification of new risks by on-body data gathering to detect unknown and synergistic risks. The automated notification of accidents and near-misses (viz., possibly nocive or even deadly events that occurred but did not cause any harm) also allows regulatory governmental bodies to identify dangerous situations systematically underrepresented in the industries' self-reports.

Reconfigurable WBAN including a variety of sensors can allow for monitoring risks in the workplace. These systems can include a companion app to report events and the use of machine learning (ML) techniques [39]. The next step is enriching the information from the worker body with additional environmental sensing or communication checks, to implement more comprehensive context-aware systems for risk monitoring [42,43]. Similarly, it is possible to achieve automatic detection of near-misses; reference [46] describes the deployment of a software-defined radar monitoring the workzone. By collecting radar data and merging them with additional contextual information, it is possible to recognize near-misses, for example, in the case of railroad maintenance (as depicted in Fig. 3(c)). Even if the identification of new risks thanks to the gathered data is theoretically possible and it is the main objective of near-misses reporting, no investigation towards this goal has been reported yet.

4. Supporting the Occupational Activity

The OSH goals can also be pursued by implementing different procedures or introducing new devices to support occupational activity (Table 1). As an example, robots can operate alongside workers to reduce the biomechanical workload of line operators. The support of occupational activity is an applicative pillar of utmost interest for the BASOSH framework, since it includes localization and ad-hoc links, wherein the interrelationship EM-body-OSH is oftentimes addressed during the design of the physical layer. However, it is still done partially and in a case-by-case basis, hindering any possible direct comparison between similar works.

4.1. *Workers' Localization and Access Control*

Workers' localization and access control (which is straightforwardly implemented from tracking) can be in principle coupled with other applications (e.g., telemonitoring) thanks to information such as the RSSI (received signal strength indicator) and unique identification string. Hence, this section is restricted to works explicitly dedicated to one of the two target applications, excluding works comprising multiple uses, such as [32].

Radiolocation has a long history and a wide range of techniques and protocols that can be chosen [85]. In the BASOSH domain, the constraints related to work determine the possible design choices; therefore, the most utilized wireless technology in the literature is RFID [48,49,51,53], which exploits low-cost body-worn tags, but studies employing BLE [50], Wi-Fi [54], GNSS [55], or combined LiDAR-UWB (light detection and range; ultra-wideband) [52] are also reported. Even other protocols are preferred in harsh work environments, such as LoRa for SaR missions (see next Sec. 4.2). Location-based risk assessment is a natural extension when contextual information is accessible at the system level, for example, monitoring artificial ventilation in the tunnel near the locations of workers [54]. All of these investigations do not consider formally the design limitation posed by the workzones that carry a risk factor, simply implying them as part of the engineering problem to be avoided altogether. This is a limiting approach in real use-cases, since a significant decrease in risks and harm can be obtained with suboptimal solutions that are ready to be implemented.

4.2. *Ad-Hoc Communication Links*

Occupations in challenging environments, such as mines, forests, or search-and-rescue (SaR) scenarios, easily induce communication disservices, posing severe risks for such workers. They also constitute propagation scenarios still little explored due to rare geographical areas (mountain canyons, through-the-snow links...) and high-risk conditions (extreme temperatures, high-mobility radios...). Automation, like the use of UAVs (unmanned aerial vehicles), can introduce further complexity in the scenario. Therefore, a growing literature is dedicated to characterizing precisely these links, wherein the coupling

between the electromagnetic fields, the workplace, and the human body cannot be addressed by separating the three logical blocks. Work-optimized links analyze communications in static workplaces such as mines [57,59], railroads [58], and industries [56]. They apply standard radiopropagation studies to highly-specific occupational scenarios wherein generic standards are not valid. Disaster management works especially focus on high communication quality [60] or specialized antenna design [63]. In-clothes antennas to optimize ad-hoc off-body communications are designed by textile integration [64,65] (Fig. 4(a)) and then possibly enriched with dual-polarization [66] or receiver diversity [67]; epidermal antennas are not taken into consideration due to their inferior EM performance, even though their minimal invasiveness could be precious for indoor applications. Off-body links involving UAVs (a.k.a. body-UAV links) are worth a specific mention, as they contextually characterize the movements of the individual and the UAV in peculiar scenarios such as Mediterranean forests [68] or snow-buried transmitter [70]. Radiopropagation of body-UAV links are currently modelled through experimental campaigns, and still lack a dedicated theory.

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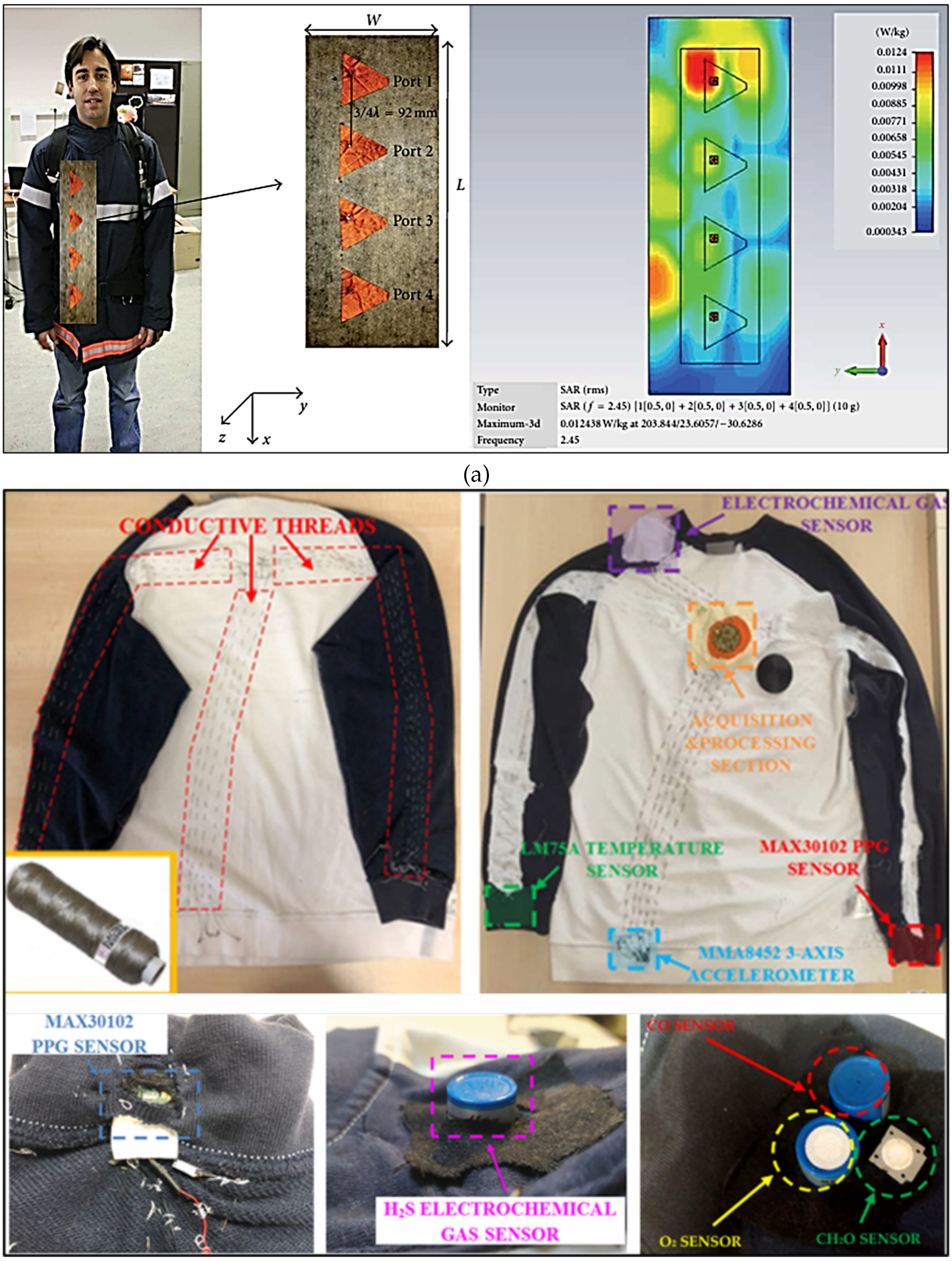

(a)

(b)

Figure 4. Examples of applications for supporting the occupational activity. (a) Antenna integrated into protective clothing and numerical evaluation of its SAR (adapted from [64]). (b) Sensorized shirt for monitoring environmental hazards (adapted from [79]).

4.3. Increasing Work Efficiency

Working efficiency can be greatly increased by curing the workers' well-being or introducing alongside workmen automated workforce, i.e., cobots and robots. Reference [86] states that a "collaborative robot (cobot) is a robot that can interact safely in close spatial and temporal proximity with humans on shared tasks-enabled through environment sensing and autonomous decision making". This Subsection follows this distinction; consequently, robots for operations at distance are included next in Sec. 5.2.

Grapplers for assembly alongside humans are the cobots more recently investigated [71,72,74]. They usually have a set of pre-programmed movements and are sensorized to react to human activity, for instance, by using a wireless ring for activation [72]. Skulji *et al.* proposed tracking worker movements via BAS to automatically control the very movements of the cobot arm [73]. The working robots are designed to be more autonomous: agricultural automated robots can work in the fields and react to the proximity of humans wearing a radio frequency beacon to avoid accidents [75,76]. Monitoring workers' physical [78] and cognitive well-being [77] is also an effective method to increase job satisfaction and improve work efficiency. All these reports are mainly dedicated to the OSH domain and deprioritize the bodycentric wireless layer.

4.4. Gathering Additional Environmental Information

BAS can also return to the user additional environmental information that would otherwise be inaccessible, so to empower new work tasks and procedures, increasing efficiency beyond the known risk to be monitored (included previously in Sec. 3.3). Body-worn sensors can return information on the eventual presence of chemical gasses [80,81] and physical hazards such as extreme temperatures [79] (Fig. 4(b)). Thanks to sensorial ultrability systems (i.e., systems that return to the user an additional artificial sense [84]), workers can even perform novel jobs by sensing differences in quantities such as magnetic fields [83] or dielectric permittivity [82], which is widely studied in the food industry for assessing food quality and preservation [87]. It is worth noting the deep relationship between sensorial ultrability and the Tactile Internet paradigm [88], which is expected to play a major role in the future industry even if it is currently at the conceptual stage. Thus, returning operators previously unaccessible environmental information can potentially achieve multiple OSH goals, but research on the topic has still very low TRL (technology readiness level).

Table 2. Bibliographic table on preventing accidents, mitigating risks, rehabilitation, and prosthetics.

Class of Application	Application	Details	References
Preventing accidents and mitigating risks	Extended Reality	OSH training	[89,90]
		Smart operator	[91,92]
		Workplace design	[93]
	Remote robots	Remote control	[71,94–97]
		Context awareness	[98]
	Ergonomics	Biomechanics	[99–103]
		Movements tracking	[104,105]
		Microclimate	[106]
		Neuroergonomics	[107]
	Compliance with safety measures	Organizational measures	[108–110]
		PPE maintenance	[111]
Rehabilitation and Prosthetics	Rehabilitation	Occupational therapy	[112–115]
		Exoskeletons	[116]
	Prosthetics	Prosthesis control	[117–119]

5. Preventing Identified Accidents and Mitigating Risks

Technological evolution is increasingly improving virtualization and prediction methods to prevent likely accidents and long-term health consequences (Table 2). Whereas the previous Sections focused on health monitoring and enhancing the vocational activity, in this applicative pillar, we focus on *i*) virtualization and automation that remove the physical presence of the worker altogether, and *ii*) organisational measures that ensure ergonomic and safety compliance. Specularly to the first applicative pillar, this Section primarily focuses on the OSH consequences of the systems neglecting the wireless layer, resulting again in a partial BASOSH integration.

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5.1. Extended Reality

XR (extended reality) is an umbrella term that encompasses augmented (AR), mixed (MR) and virtual reality (VR). According to [120], AR allows the worker to see the world together with virtual objects, MR creates a space where real and virtual objects influence each other, and VR is immersive technology to interact with computer-generated three-dimensional environments. It is evident that XR can significantly enhance the work experience and will be integrated into future workflows.

The most immediate application is the use of VR WBAN with sensors and gloves for OSH training in dangerous vocations such as side-road [89] (Fig. 5(a)) and live-line [90] operations. Beyond technological challenges and despite promising results, VR for OSH training remains a highly-debated topic, with multifaceted issues (ranging from high costs to lack of digital content and social acceptance) yet to be addressed [121]. Empowering workers during their activities according to the "smart operator" model was proposed by using VR to enhance agile working [91] or AR to interact with machines through digital twins [92]. VR was also tested for designing cobot workspaces, by programming the expected cobot's movements [93] (Fig. 5(b)). The recent review on VR applications for designing workspaces is worth mentioning [122] even if it has a tangential focus w.r.t. the present article as the wireless layer is considered given. All reports in this research area are currently trying to quantify the benefits of this very recent approach and produce a high potential for innovation, neglecting again the overall system optimization.

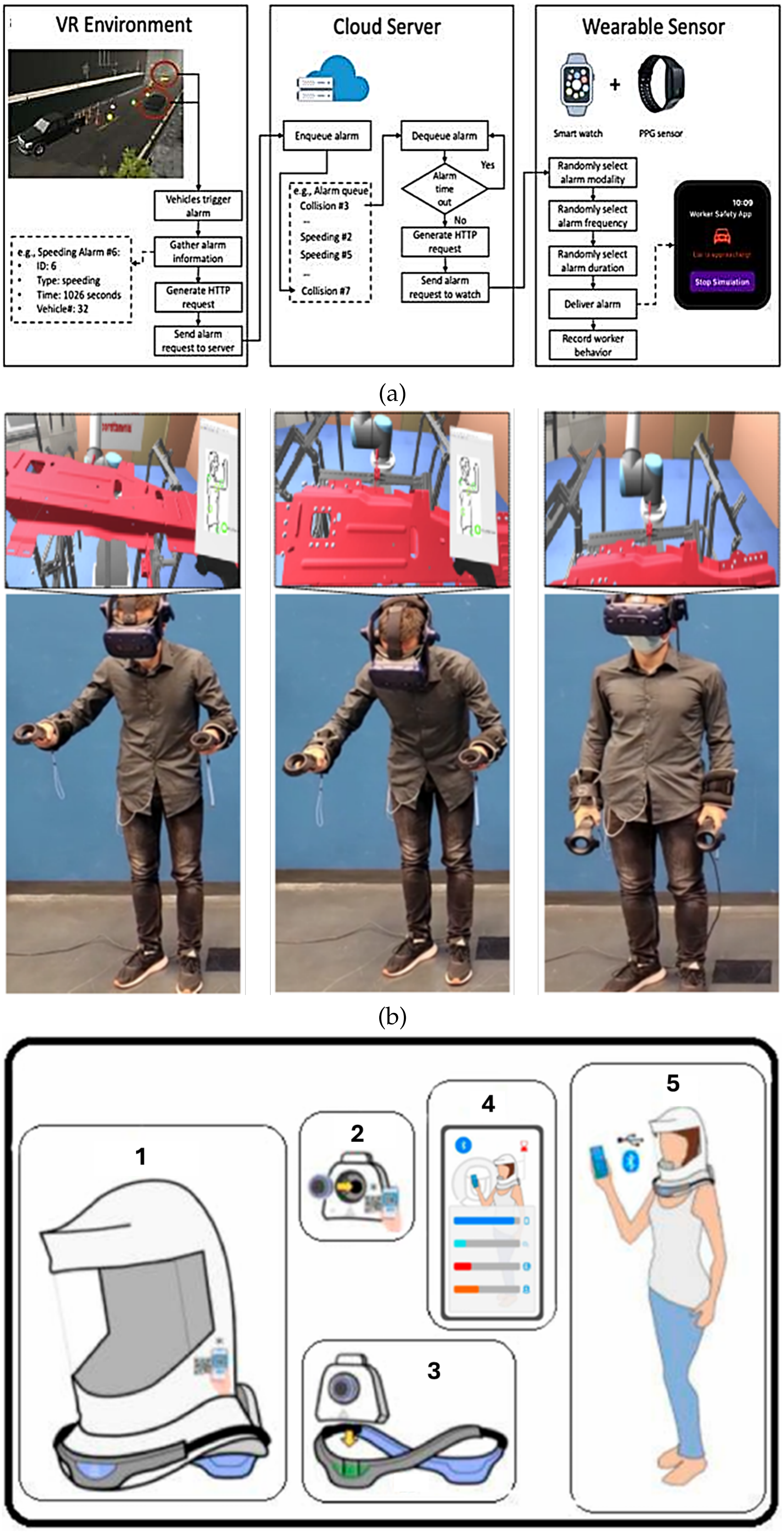
5.2. Robots for Remote Operations

Unlike cobots and robots designed to operate side by side with humans, teleoperated robots can shield workers from harm thanks to remote operations and contextual awareness. EMG controls can be used to control robotic arms at distance; ref. [71,94,96] exploit BLE wearables to pilot a single arm, while Wang *et al.* [97] consider a dual-arm robot capable of automatically avoiding self-collision. In recent years, 3D-printing is also being investigated for producing these robots, paving the way for wide adoption [95]. Larger system architectures connecting such robots with context-aware wireless networks (involving sensors and possibly workers' WBANs) have been proposed [98], but no implementation has yet reached relevant development or deployment in actual OSH scenarios.

5.3. Biomechanical and Ergonomic Assessment

Ergonomics concerns the understanding of interactions among humans and other elements of a system, to optimize both human well-being and overall system performance [123]. It is fundamental for OSH, encompassing biomechanical (mainly for improved comfort, stress reduction, and prevention of musculoskeletal diseases) and microclimatic assessments (concerning the exchange of heat in the worker's proximity).

The most commonly used methods for biomechanical risk evaluation currently utilize direct observation and/or video recordings [124]. Wireless IMUs can allow for more precise measurements on-site directly during work activity [103], eventually enriched with EMG data [99,101,102] and even ML techniques [100]. This first set of studies uses standard wireless sensors and focuses on OSH applications. Another set of studies focuses on the optimization of the wireless layer for movement tracking without being directly entangled in biomechanical assessments [104,105], providing the specular viewpoint of the previous set. In the literature, a complete analysis of both the design of the bodycentric system and its consequences on the precision of biomechanical risk evaluation is still missing. A more holistic approach was used for microclimatic ergonomics; indeed, in a recent work, Li *et al.* designed a system to predict the microclimate needs of the workers and adjust the air conditioning and ventilation accordingly [106]. Lastly, since BAS including wearable neurotechnologies are a fundamental enabler of neuroergonomics, BASOSH and this emerging research topic are deeply intertwined [125]. Very recently a wearable system was presented at a conference to track and minimize workplace stress [107], demonstrating the potential of this specific application.



(a)

(b)

(c)

Figure 5. Examples of applications for preventing known accidents and mitigating risks. (a) Architecture of a VR environment for OSH training (adapted from [89]). (b) Effectiveness assessment through VR during the design of a workstation with cobots (adapted from [93]). (c) WBAN monitoring the correct PPE procedure (adapted from [111]).

5.4. *Compliance with Safety Measures*

One of the main causes of work accidents and casualties is the lack of compliance with safety measures to mitigate risks, be it organizational measures or PPE compliance. Bodycentric wireless systems can monitor the compliance with safety measures in real-time, provided that the necessary contextual information is available. For example, lone-workers can be the target of specific organizational measures and should be monitored [108], as well as operators exposed to a higher risk of collisions on the job [109,110]. For this application, wireless devices must be strictly integrated with the organizational procedures that are further refined on the basis of the sensorized data available (e.g., keeping a distance from the machines as suggested by the body-worn system). Accordingly, the usage of PPE can be improved even without enhancing the protective gear itself; it is sufficient to communicate wirelessly with an optimal smartphone app to ensure that the user knows and follows the optimal maintenance and wearing steps [111], as illustrated by the filtering facepiece respirator in Fig. 5(c). It is worth remarking that ref. [111] develops a dedicated communication protocol to achieve robust communications in the specific scenario, implicitly following the unitary framework "wireless communication-body area-OSH goal". This specific application is technologically mature, and authors are currently testing adoption in real case-studies.

6. BASOSH for Rehabilitation and Prosthetics

Rehabilitation and prosthetic applications constitute the least investigated and applicative limits of BASOSH, since the third logical block (OSH application) is implied by their generic nature. By strict definition, BASOSH are limited only to occupational therapy for work-related tasks and specialized prostheses for vocational purposes [126,127]. In this work, these BASOSH applications are included anyway for the sake of completeness (Table 2), since, although they have not yet been fully developed, research is quickly convergent towards refined therapies aimed at work environments [128] and wireless prostheses [129]. BASOSH addressing these applications can hence be expected to be considered and proposed in the next few years, with the potentiality of revolutionizing current approaches. Even though the reports in this application are few and the BASOSH integration is still missing, the unitary nature of the OSH issue and the bodycentric wireless design is self-evident in the existing literature.

6.1. *Rehabilitative BASOSH*

Rehabilitation of injured workers is a medical issue strictly related to the OSH domain. Occupational therapy, in particular, by focusing on the execution of specific tasks, can be applied directly to vocational purposes. BAS can therefore be used during occupational therapy to precisely monitor movements [112], check patients even at home during rehabilitation [115], or quantify neural responses [113,114]. Similarly, body-worn sensors can support robotic rehabilitation, as reported by Perego *et al.* in [116] as the TWINMED sensorized t-shirt transmits (via Bluetooth) ECG and EMG data during the use of a lower limb exoskeleton (Fig. 6(a)). Thanks to the recorded data, rehabilitation outcomes are expected to improve greatly, potentially becoming a standard rehabilitation approach. This rehabilitation research is mainly carried out by physicians and practitioners, so that it often fails to integrate the technological perspective.

6.2. *Prosthetic BASOSH*

By broad definition, prostheses substitute body structures to reintegrate lost biological functions. Wireless EMG are used to control prostheses in research, refine movements for better control, holding high promises to fully reintroduce the prosthetized patient into the workforce. As an example, neuroprosthetes were designed and tested with a driving simulator to check patient alertness in laboratory settings [117]. Ref. [118] exploits the EMG signal from the sound arm to set the correct response of a myoelectric prosthesis, while a flexible glove is utilized to control an upper limb prosthesis in [119]. However, research on the topic is highly complicated by the relative rarity of patients using comparable prostheses. Perhaps the most relevant result in wireless prosthetic control is currently provided by industrial research; the HeroPRO prosthesis by Open Bionics® can be controlled remotely using the EMG signal recorded and transmitted by MyoPODS (Fig. 6(b)). The relationship between these commercial BAS and the OSH domain has not yet been addressed in research, but there is no significant technical barrier hindering this evaluation process, as elaborated on in the following.

Figure 6. Rehabilitative and prosthetic BASOSH. (a) Sensorized shirt TWINMED monitoring the patient during rehabilitation with a lower-limb exoskeleton (adapted from [130]). (b) The wireless prosthetic control MyoPods (By Open Bionics®) compatible with the upper limb porthesis HeroPRO (by Open Bionics®; images adapted from [131] and from [132]).

7. Opportunities, Challenges, and BASOSH Functional

The literature review above highlights the existence of a vital research topic that is still scattered across diversified fields. Some authors independently and partially involved OSH directly in BAS design stage even without an established formalization (e.g. [55,65,68,96,104,106,111,116]), proving the necessity of the conceptual unitary framework introduced in this article. The opportunities rising from establishing such a framework are as numerous as the applications, since the holistic viewpoint can quickly identify scientific gaps and promote advancements in the whole area. For example, there is no technological barrier to prosthetic BASOSH anymore, and OSH studies in wirelessly-prosthetized patients can be conceived and carried out in workplaces to quantify design issues, gained benefits, and residual risks. Another example is given by the role of additive manufacturing for BASOSH, which is still an underinvestigated topic with an emerging research community [13,95,133]. Moreover, by applying the unitary framework, multiple applicative pillars can be pursued by the same wireless system; for instance, the first and fourth applicative pillars could converge soon. Indeed, cyber-prostheses were recently defined as prostheses including wireless sensing capabilities to return health data directly from the inside of the human body [134], allowing for monitoring the prosthetic effectiveness and health status of the prosthetized worker.

Naturally, several challenges remain, including technological and conceptual limitations. On the technological side, we can swiftly recognize the need for biocompatibility for implanted devices, structural durability in harsh environments, and the need for multiple 3D-printing techniques to achieve personalization, flexibility, and functional integration (resolution limitations, potential retention of harmful substances). On the conceptual side, we must address performance conflicts (such as combining metallic components for osteointegration with conductive elements for wireless communication), and the need of tailored metrics for the design of BASOSH (viz., design function linking directly the on-body electromagnetic parameters and the goal OSH functions; for instance, weighting communications outages by the expected risk in the specific workzone). In fact, in order to optimize the systems for multiple goals simultaneously, there is the necessity of system-level electromagnetic design approaches, like joint-design (which can be defined as the simultaneous optimization of multiple subsystems [135,136]), co-design (which can be defined as an iterative design method wherein the subsystems are designed in sequence [137,138]), constrained design (wherein the parameters' space is limited by external conditions [139,140]), and numerical-statistical methods (that stimulate numerically multiple scenarios to derive statistical analyses [69,141]).

Therefore, the case-by-case approach currently employed in the scientific literature has evident limits and should be overcome to foster scientific advancement in the domain. In the author's opinion, the development of unitary metrics and their use in selected case-studies for designing bodycentric systems should be the initial step towards the next generation of bodycentric antenna systems for vocational purposes. These metrics for optimizing the systems are here formalized in mathematical terms without loss of generality, in a parametric functional form named "BASOSH cost functional":

$$\Upsilon_{BASOSH}(\mathcal{F}) = w_1\varepsilon(\mathcal{F}) + w_2\beta(\mathcal{F}) + w_3\omega(\mathcal{F}) \tag{1}$$

where Υ is the actual BASOH cost function to be minimized when designing the system, $\mathcal{F}$ is the vector of the design parameters to be optimized, $\{w_1, w_2, w_3\}$ is a set of weights, ε is the function of the EM and communication performance (radiation efficiency; realized radiation gain; packet delivery ratio; quality of service...), β is the function that accounts for the presence of the human body (specific absorption rate, SAR; postures; intra- and inter-user variability; usability...), and, finally, ω is the function that quantifies OSH constraints and goals (residual risks; avoided harm; comfort improvement; heightened efficiency; report accuracy; movements' recovery...). Whereas the BASOSH functional presented here is at a general level, its purpose is to provide a unifying design language rather than a prescriptive optimization algorithm, whose instantiation is necessarily application-specific. As a simplified example, let us consider a body-worn wireless sensor monitoring the presence of noxious substances with a programmable transmit power and duty cycle; increasing the transmission power could minimize the bit error rate (lower ε), but increase the SAR (higher β), leading to a lower duty cycle that could increase the overall risk because of lengthened off-time (higher ω). The choice of the weights by the designer is hence vital in optimizing such a system, and it should be carefully selected based on the designer's expertise. By applying the BASOSH functional at the design and/or evaluation stages, it will be possible to contrast similar systems in a quantified way, allowing for a direct comparison that is currently impossible and necessary to systemize the field.

8. Conclusions

In this review, the state-of-the-art of bodycentric antenna systems for occupational safety and health was explored and categorized into four applicative pillars. Even though the addressed issues have recurring aspects (strict design constraints, major impact of human postures and movement, etc.), most contributions do not consider simultaneously the three BASOSH components (wireless layer, human body coupling, vocational constraints), confirming the lack of integrated design approaches. On the basis of a few studies converging towards a unitary viewpoint and the authors' experience in the topic, some opportunities and challenges of these systems were outlined. In the end, a class of functions named "BASOSH functional" was proposed to design and compare such systems, aiming at systemizing the sparse research domain.

Recognizing BASOSH as a research domain and adopting a holistic design approach is both an academic and an applied scientific challenge that involves vital consequences in the near future. If the scholar community can identify, address and overcome the multifaceted issues of this research domain, the ideal of *personalized OSH* tailored to the needs of the specific worker will greatly advance and improve working conditions worldwide, and for everyone.

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Abbreviations

The following abbreviations are used in this manuscript:

AR	Augmented reality
AS	Antenna systems
BAS	Body-centric antenna systems
BASOSH	Body-centric antenna systems for occupational safety and health
B-IoT	Bodycentric Internet of Things
BLE	Bluetooth low-energy
ECG	Electrocardiography
EEG	Electroencephalography
EM	Electromagnetism (or electromagnetic)
EMG	Electromyography
FAD	Finger augmentation device
GNSS	Global navigation satellite system
LiDAR	Light detection and ranging
R-FAD	Radiofrequency finger augmentation device
ILO	International Labour Organization
IMU	Inertial measurement unit
ML	Machine learning
MR	Mixed reality
OSH	Occupational safety and health
PPE	Personal protective equipment
RFID	Radiofrequency identification
RSSI	Received signal strength indicator
SAR	Specific absorption rate
SaR	Search-and-rescue
TRL	Technology readiness level
UAV	Unmanned aerial vehicle
UHF	Ultra-high frequency
UWB	Ultra-wideband
VR	Virtual reality
WBAN	Wireless body-area network
XR	Extended reality

Appendix A. Scientometric Investigation and Methodology of the Review

The literature survey was carried out adopting two different approaches. ScientoPy scientometric software ([142]) was used in the first approach to identify BASOSH applications in the core of the scientific databases Web of Science (WOS) and Scopus. The second approach consisted of scouting Google Scholar to find additional interesting publications for the identified applications. The works were excluded based on their abstract and in-depth reading and evaluation in light of the BASOSH framework. Patents (e.g., [143–145]) were not organically considered in the scientific review, and papers that could not be accessed were not included in the survey based on Table 1 and Table 2. The databases were lastly browsed on April 18, 2026, for updated ScientoPy[1] processing

In the first approach, the databases were queried using a composite string representing the three logical blocks identifying a BASOSH, as written in Sec. 2: for the EM physical layer, the block was

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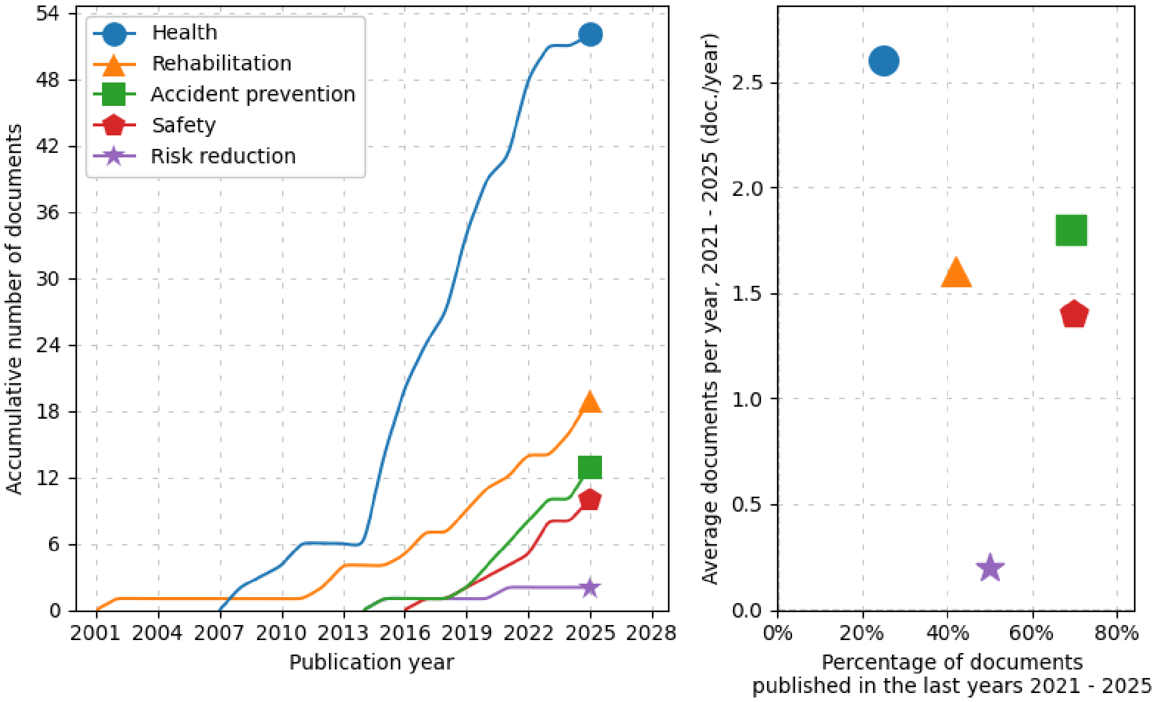
[1] https://github.com/jpruiz84/ScientoPy

{"WIRELESS" OR "ANTENNA" OR "RADIOWAVE" OR "WBAN"}; for the human body involvement, keywords were {"WEARABLE" OR "BODY-CENTRIC" OR "BODYCENTRIC" OR "ON-BODY" OR "IMPLANTED" OR "BODY SHADOWING" OR "PROSTHESIS"}; for the OSH application, {"WORKER" OR "WORKPLACE" OR "VOCATION*" OR "OCCUPATION*" OR "SPORT"} was used. The {AND} logical operator connected the three textblocks. Since the BASOSH field of study is strongly variegated and scattered, this approach underrepresents the actual research domain, investigated by the survey through the second approach. However, this restrictive search was selected to identify the presence of a core literature that actually demonstrates the presence of an unnamed field of research here formalized in the BASOSH framework. The first approach omitted all documents that were not journal or conference articles or reviews. Duplicates between databases were also removed. In the end, 1110 records were used for trend analysis (Table A1).

Table A1. ScientoPy processing of the databases results.

Database	All results	Removed by type	Removed duplicates
SCOPUS	1079	852	845
Web of Science	422	265	265
Total	1501	1117	1110



(a) (b)

Figure A1. Scientometric processing of the retrieved records.

Five keywords were selected to analyze historical trends in the restricted set of reports: HEALTH, REHABILITATION, ACCIDENT PREVENTION, SAFETY, and RISK REDUCTION. Although the set cannot fully describe the precise evolution of the BASOSH field, we can state that this research line was born in the first 2000s, focusing first on health monitoring and rehabilitation. Only after 2010 have the aspects related to greater prevention of harm gained traction, probably fostered by more widespread sensors (Fig. A1(a)). Fig. A1(b) restricts the analysis in the last five years (2021-2025); overall, all BASOSH applications show vitality in the restricted dataset, with {"RISK REDUCTION" + "SAFETY" + "ACCIDENT PREVENTION"} returning promising growth. However, in the absence of a recognized field of research, the scientometric tool used can only provide a qualitative analysis, here useful for setting the literature survey and conceptualization of the area.

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