Modernizing Occupational Safety in Industry 4.0: A Review of State-of-the-Art Safety Wearables

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Industry 4.0 signifies a paradigmatic transformation in occupational safety, paving the way for the safety wearables (SWs) market, which is still in its early stages in Brazil. This study aims to comprehensively review the global state of the art of safety wearables, compiling pertinent technological trends for the country's reindustrialization debate. Articles were sourced from the Scopus platform, and VosViewer was utilized for keyword tracking. A global race of SWs research is evident, with the construction industry at the forefront, emphasizing monitoring employees' mental states. The emergence of local startups in Brazil within this theme is expected in the forthcoming years, potentially contributing to reducing the high rate of work-related accident mortality in the country.
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Introduction

Intending to gather development strategies to assist the modernization of Brazilian industry in the face of 21st-century challenges, the National Confederation of Industry published the document entitled "Industrial Revitalization Plan" in May 2023 [1]. Proposal 57 of this Plan mentions implementing new occupational health and safety regulatory standards (NRs) and initiating a monitoring process to achieve greater effectiveness in reducing occupational risks and accidents. The goal of this proposal is commendable, especially when considering the national context of occupational accidents. According to the International Labour Organization (ILO), Brazil ranked second among the G20 countries in work-related mortality in 2020 [2].

An issue that the occupational safety area still encounters in industries operating in large areas and/or with a large number of individuals is individual worker supervision. This monitoring is paramount since, in an industrial setting, unsafe behavior can lead to an unsafe condition for other workers (reduced reliability process). In this context, the concept of human error emerges. According to Sanders and Moray (1991), "human error is a decision or behavior that reduces or has the potential to reduce the safety or performance of a system" [3]. This panorama is similar to activities carried out by machines since they were previously programmed by humans and, in operation, they work in a man-robot collaboration. Thus, the need arises for measures not only of prevention (e.g., personal protective equipment, occupational health and safety regulatory standards, and training) and monitoring and interpretation of patterns (of use and execution). Therefore, having a database regarding worker behavior allows for the creation of patterns and their categorization, that is, screening, as a filter, whether the individual is fit for work. The technological advancement capable of performing this function is through safety wearables (i.e., intelligent wearable devices capable of collecting and analyzing data and providing feedback to the user) [4]. The growth of research related to SW in the global scenario is evident. The individual monitoring of workers and interpreting their results are becoming increasingly necessary to ensure safe working conditions in line with this new paradigm of industrial digitalization. Therefore, this article aims to conduct a state-of-the-art review of SWs, mapping the principal

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countries, emerging technologies in the market, promising areas, and critical authors. The goal is to compile these trends and analyze them in the context of Brazil. Thus, this work seeks to contribute to discussing the modernization of the occupational health and safety field in the context of the new Brazilian industry.

Materials and Methods

The articles analyzed in this study, extracted from the Scopus platform, resulted from a search using the keywords "safety and wearables*" in the abstract, keywords, and title. The inclusion criteria for this research encompassed documents in English and of the type "article." The search was conducted in May 2023 and yielded 2,027 results; however, only the documents from the top five authors were individually examined.

The articles were read and categorized in an Excel spreadsheet (Main Spreadsheet) according to their respective application areas. The purpose of this spreadsheet was to compile patterns, classifying the information extracted from reading the abstracts and the full articles into nine categories (e.g., author, title, area, technology, classification, device, sensor, and biological systems). The criterion for the "classification" category was based on the work of Jabelli and colleagues (2019) [5].

The VOSviewer platform was used in this study to conduct a broader review, encompassing all the results from the search of the main terms mentioned in the 2,027 publications. For the compilation of the graph, a co-occurrence analysis was chosen using the fractional counting method, and the inclusion criterion was a minimum of 30 repetitions of keywords. Additionally, the platform was used to verify if the patterns found in the Excel spreadsheet (Main Spreadsheet) covered the keywords and trends of the entire dataset. In other words, to assess whether the author's microanalysis was consistent with the results of the macro-level analysis.

Results and Discussion

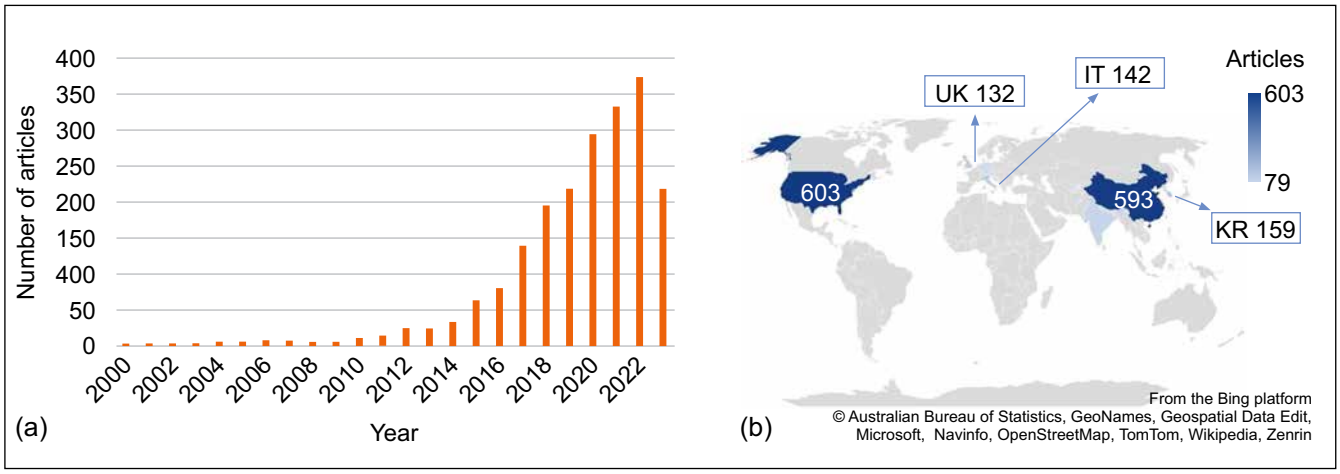
During the study of articles from the top 5 authors, a notable emphasis was observed on chemistry with 22% of the publications (batteries), and 78% in the construction industry. Consequently, a more specific criterion was chosen for further analysis. Therefore, the publications related to the construction industry were compiled in the Excel spreadsheet (Main Spreadsheet). This Excel data and Scopus platform information generated graphs for temporal evolution, main classifications, and top publishing countries.

Temporal Evolution and Key Players

The temporal evolution of published articles from 2000 to 2023 was obtained from the research results. The average publication, with 5-year intervals, ranges from 3 publications (i.e., from 2000 to 2004) to 139 (i.e., from 2015 to 2019). Analyzing the Figure 1, we evidenced that the set of Industry 4.0 incentive programs reflects the advancement of the scientific community. Since 2015, countries such as China, South Korea, the United States, and the United Kingdom have invested approximately R$1.2 trillion in policies focused on digital transformation, science, technology, innovation, decarbonization, and more [1].

On the other hand, it is observed that Brazil currently does not occupy a prominent position in this field and still demonstrates very incipient research efforts. However, given three key factors, the country presents fertile potential for developing this area: domestic investment, abundant raw materials, and an innovation ecosystem. Firstly, the resumption of public policy discussions focused on the domestic industry is paramount. Secondly, Brazil's expertise in silicon extraction and purification processes generates a more stable and appealing context for the global economy, especially when combined with the fact that the country holds approximately 95% of the world's

Figure 1. Number of publications per year (a) and key publishing players (b).



quartz deposits [6]. Lastly, the stakeholders in this ecosystem, including research centers such as universities and federal institutes, as well as companies like the National Center for Electronic Technology (CEITEC), play a crucial role. CEITEC, a state-owned company specializing in sensor and integrated circuit development, is a potential player for SW (Silicon Wafer) projects. CEITEC boasts extensive market experience, with semiconductor applications focused on cryptography, wireless communication, and security, among others [7].

Classifications and Main Devices

Figures 2 and 3 demonstrate the results obtained when analyzing the classification groups and the primary devices mentioned in the articles. Notably, the monitoring of workers' mental state received significant attention within the category of articles. It occurs due to the association between brain activity and stress, concentration, or enthusiasm levels and how its analysis yields accurate data. The worker's mental state is essential even in human-robot collaboration activities [8]. In line with this finding, the primary device mentioned is the electroencephalogram (EEG), capable of reading cerebral electrical activities.

VOSviewer (Keyword Clusters)

The Figure 4 generated in the VOSviewer platform [9] demonstrates that the trends found in the macro-level analysis confirm the trends of the micro-level analysis. In other words, even when analyzing a subset of 39 works, the patterns found in this research also stand out when viewed as a whole. The construction industry field obtained an average of 48.5 occurrences, with the main keywords being "construction workers" and "construction safety." Among other significant results, there is the appearance of the words "fatigue" (30 occurrences), "ergonomics" (54 occurrences), "risk assessment" (76 occurrences), "walking" (41 occurrences), and "gait" (49 occurrences), all related to the classification graph (Figure 2). As for the occurrences in the graphs of the devices, "textiles" (56 occurrences) and "electroencephalography" (48 occurrences) stand out.

Conclusion

In conclusion, there is a global race in research on wearable safety devices, as workplace safety is increasingly perceived as an investment. This perspective goes beyond the social aspect, emphasizing a more humane approach toward workers while recognizing the potential of these

Figure 2. Classifications.

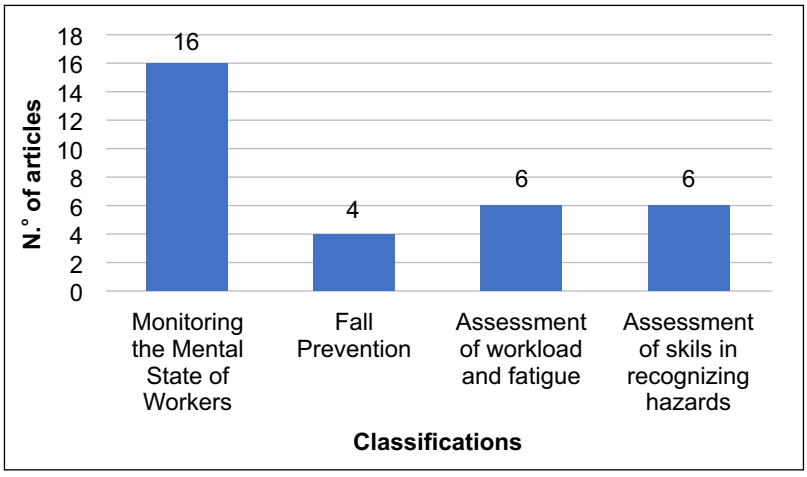
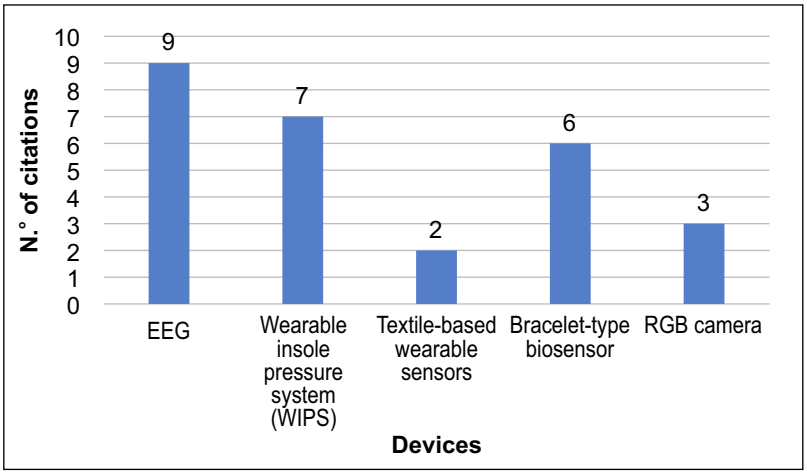
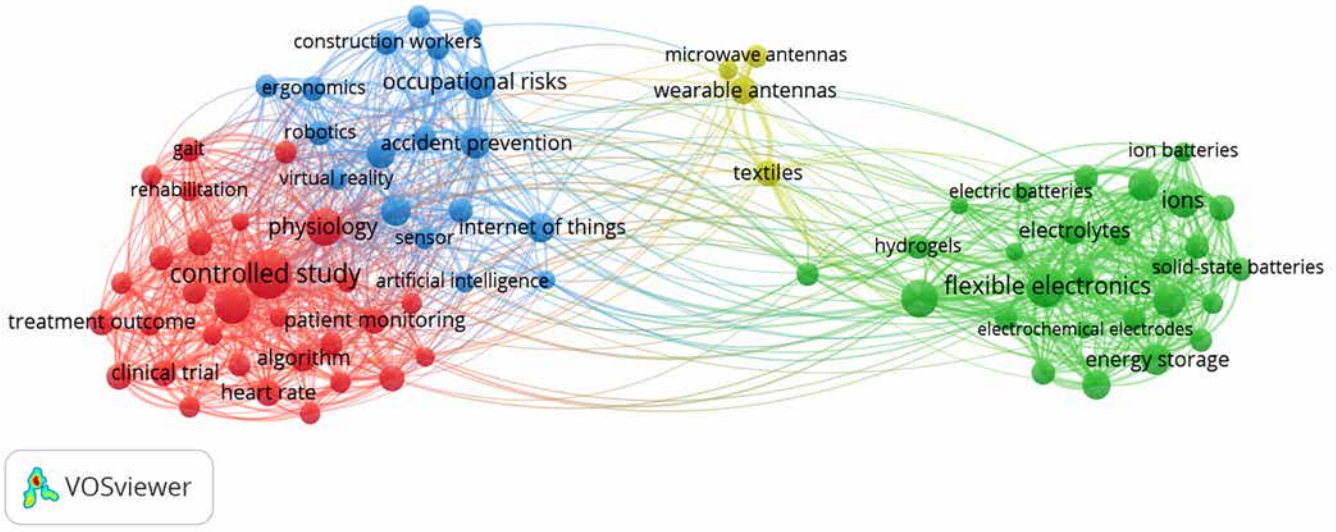


Figure 3. Devices.



devices to reduce occupational risks, misuse of machinery, and unnecessary maintenance, enhance technical operations, and create new markets for SW innovations. While SWs currently excel in the construction industry, expanding these devices to other sectors is viable to address similar safety gaps. It is particularly relevant and feasible in the national context, where incentives for industrial development, such as the Growth Acceleration Program, are increasing, and the internal scenario of accidents calls for restructuring. The four categories discussed, Monitoring the mental state of workers, Fall prevention, Assessment of workload and fatigue, and Assessment of skills in recognizing hazards, represent a latent opportunity for analyzing applications of SWs in companies, facilitating their integration, and potentially mitigating workplace accident rates. In addition, it was possible, through this research, to map the main types of devices (EEG, WIPS, Textile-based wearable sensors, Bracelet-type biosensors, RGB cameras) already used in the field of SW. Ultimately, this article provided insights into the emerging global field of SW in Brazil, especially regarding the emergence of new companies that can operate synergistically with CEITEC, fostering an innovation ecosystem to support Brazil's reindustrialization in light of the Industry 4.0 paradigm of production.

Figure 4. Map from the VOSviewer platform.



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