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Review Article

Artificial Intelligence and Technologies Applied to Occupational Ergonomics: The New Era of Scientific Ergonomics 4.0

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Abstract *- Industry 4.0, with its promise of a revolution, fuses advanced production techniques with smart technologies, benefiting both companies and workers. In this study, a systematic review was conducted to examine 4.0 technologies that improve work ergonomics. Out of 639 results, only 60 studies were selected using search algorithms. The role of virtual reality, artificial intelligence, digital twins and exoskeletons in ergonomics 4.0 was highlighted, improving the well-being of workers. 75% of the studies were conducted between 2020 and 2023, addressing aspects such as industrial process optimization, human safety, digital twins, and the use of collaborative robots and wearable sensors to improve ergonomics. These results highlight the importance of integrating 4.0 technologies into detailed analyses to improve the quality of working life and reduce musculoskeletal risks, promoting health in the work environment.*

Keywords *- Artificial Intelligence, Digital twins, Ergonomics, Industry 4.0, Virtual Reality.*

1. Introduction

Ergonomics is a human factor in engineering and design that seeks to adjust working conditions to suit people while adapting everyone to their respective work environment. The primary objective is to ensure the safety and well-being of employees, with the consequent improvement of their productivity. As a scientific discipline, Ergonomics integrates knowledge from various areas to obtain practical and applicable information. The emergence of a new dynamic human-machine interaction is based on collaboration with Artificial Intelligence (AI), which has the potential to transform the way engineers will carry out their tasks in the future [1]. The ergonomics approach is not limited to reducing risk factors, which are crucial for reducing occupational accidents [2, 3]. Its purpose is to improve the well-being and performance of employees, as well as to ensure optimal working conditions. Ergonomics becomes a fundamental aspect in the context of occupational health and safety as it seeks to establish working conditions that are optimal for employees, which in turn facilitates the effective performance of their work activities [4-6]. Today's technological advances are not able to completely replace the adaptive ability and innate executive abilities in humans. Activities that involve monotonous repetitions, such as lifting, assembling, and manipulating, as well as physically demanding tasks in repetitive and uncomfortable work positions, generate musculoskeletal disorders or injuries that adversely impact workers' health [7, 8]. The development of ergonomic solutions is found in applied research aimed at the growing working population going through the aging process. Over time, there will be significant changes in physiology as most organ systems experience a decline in functionality, increasing the risk of developing concurrent diseases [8]. The synergy between ergonomics, artificial intelligence, and wearable devices has become a cutting-edge strategy capable of monitoring disorders associated with work activities [9]. Occupational ergonomics is responsible for managing the interaction between the worker and the machinery in the work environment to ensure efficient, comfortable and safe performance. In this context, professional ergonomics focused on digital manufacturing focuses on establishing and optimizing the relationship between digital production machines and workers to achieve the highest standards of quality and performance in the workplace [10]. The evolution of ergonomics has been intrinsically linked to the demands generated by the industrial revolutions. In other words, the history of ergonomics has been shaped according to the technological trajectory, with the current era being Industry 4.0. [11]. The expression 4.0 is gaining ground in multiple areas of human activity and various fields of knowledge.

Related terms, such as Industry 4.0, Logistics 4.0, Smart Factory, Smart Logistics and Digitalization, are essential in both theory and practice today, encompassing both scientific research and economic application [12]. The progress and modernization of working conditions have generated transformations in work dynamics over time, demanding adjustments, innovations and solutions from Ergonomics. There is currently an important change: The Fourth Industrial Revolution. This phenomenon will cause substantial transformations in the configuration of work and the design of workspaces [13]. The objective of ergonomic analysis and new technologies 4.0 is to improve the design of workspaces to improve occupational safety and the elements of the physical environment. This is achieved by mitigating the negative impacts of work monotony and reducing physical and mental demands. One of the main research gaps lies in the lack of systematic studies that comprehensively analyze how these technologies can optimize ergonomic conditions in work environments.

Although previous research has addressed individual aspects of ergonomics in the context of Industry 4.0, there is a lack of studies that comprehensively compare the benefits and limitations of these emerging technologies in improving worker safety and performance. In addition, ergonomic risks associated with repetitive tasks, awkward postures and intense physical exertion remain a latent problem, underlining the need to develop innovative approaches and technological solutions adapted to the diversity of working conditions. Technological advances have not completely replaced human beings' adaptive capacity and innate abilities to execute specific tasks. The repetitiveness of certain activities, such as lifting, assembling or manipulating objects, continues to generate musculoskeletal disorders that affect workers' health. In this sense, the use of wearable devices, AI, and digital tools offers an unprecedented opportunity to monitor and mitigate these ergonomic risks.

However, current research has not yet comprehensively addressed the combined impact of these technologies on improving well-being and work performance. This article aims to propose a common definition and characterize the application of virtual reality, artificial intelligence, digital twins and exoskeletons in the field of ergonomics through an exhaustive systematic review of the literature. Section 2 is devoted to carrying out such a review, while section 3 details the methodology used to determine the number of studies considered in the literature review section. In section 4, a bibliometric analysis is carried out to identify patterns in publications related to the topics investigated in this study.

2. Literature Review

2.1. Ergonomics and Virtual Reality

The rise of the fourth industrial revolution has prompted most companies to adapt technologically, integrating new digital tools, such as the use of virtual reality haptic glasses with *Oculus Rift* and *HTC Vive* controllers. This technology not only contributes to preserving the integrity of workers but also leads to cost reduction and effective training of human resources in the industrial sector [14]. Organizations face limitations in terms of learning opportunities throughout their value chain due to the constant variability of the environment around them. Implementing changes during production execution becomes a complicated task, as it involves the risk of compromising the quality, safety and efficiency of the production line and the well-being of the workers, which is unacceptable. To address these challenges, Industry 4.0 has emerged, which seeks to improve processes and increase productivity in various industries. In this context, technologies such as the Industrial Internet of Things (IIoT), artificial intelligence and vision, as well as Virtual Reality (VR) and Augmented Reality (AR) have been used to achieve these goals [15, 16].

Virtual Reality (VR) is a computer-generated multimedia experience capable of digitally recreating entire design environments (Figure 1). It empowers the user to interact with all the elements present in that environment, whether they are products, machinery or production lines. The convergence of virtual reality, simulation techniques, and 3D printers has led to the virtualization of the real environment, which has led to the fading of reality. In the workplace, this transformation has not only reduced risks but has also anticipated potentially dangerous work activities for workers [17, 18]. In manufacturing, the adoption of 4.0 technologies, such as Virtual Reality (VR), has made it possible to carry out ergonomic assessments. However, its potential in terms of performance has yet to be fully explored. Remarkable growth is projected in the global market, with projections pointing to growth from $6.3 billion in 2021 to approximately $84.09 billion in 2028. This increase is attributed to the combination of cost reduction and improved quality of Virtual Reality (VR) devices, which could become indispensable for various engineering processes, thus supporting daily activities in this field. [19-21].

Fig. 1 Virtual reality experience

Musculoskeletal Disorders (MSDs), such as bone fractures, sprains, strains, ligament tears, or those linked to problems in the blood vessels of the arms and legs, are considered to be one of the main complications associated with manual labor. In Europe, they account for approximately 33% of all work-related injuries and illnesses resulting in days off work, according to a study by [22]. In Mexico, the most common diseases in this area include dorsopathies, enthesopathies, carpal tunnel syndrome, bursitis, epicondylitis, and shoulder injuries. Its treatment and prevention generate significant costs for employers worldwide. In order to prevent musculoskeletal diseases and disorders among workers, companies are carrying out ergonomic risk assessments such as the OCRA (Occupational Repetitive Action) checklist, RULA (Rapid Upper Limb Assessment) stress assessment, REBA (Rapid Entire Body Assessment), physical load assessment, frequency and severity of OWAS (Ovako Working Analysis System) risks, Body segment length estimation LSC (Length of Body Segments) and Rapid Postural Assessment (EPR).

In the automotive sector, these assessments have already begun to be implemented in each work area. The reliable detection of poor ergonomics in work postures is also being achieved using virtual reality technology and digital human models, which allows for the efficient optimization of work processes [23]. The application of innovative technologies not only supports ergonomics but also drives substantial improvements in the design of the manufacturing process, suggesting vast potential for leveraging disruptive technologies such as virtual reality [24].

Although 4.0 technologies are transforming the industry, the late identification of problems in assembling ergonomic components during manufacturing affects operators' well-being and productivity. In addition, correcting these problems leads to high costs. Virtual Reality (VR) emerges as a key tool for refining the digital human model. However, a lack of understanding of effectively integrating these technologies limits their maximum use in ergonomic assessment [25].

Consequently, ergonomics stands as a fundamental pillar in production, exploring the interrelationship between the physical aspects of individuals and work environments. This analysis encompasses human anthropometry, physiology, anatomy, and biomechanics, among other factors [26]. Thanks to the potential of virtual reality to improve factory designs before they are built, it is possible to achieve significant savings with well-crafted designs that can reduce operating costs by up to 50%.

In addition, the optimization of manufacturing processes and activities is another area where virtual reality can provide substantial benefits [27]. Another tool that has helped determine the comfort of postures is the Work Posture Analysis System (OWAS).

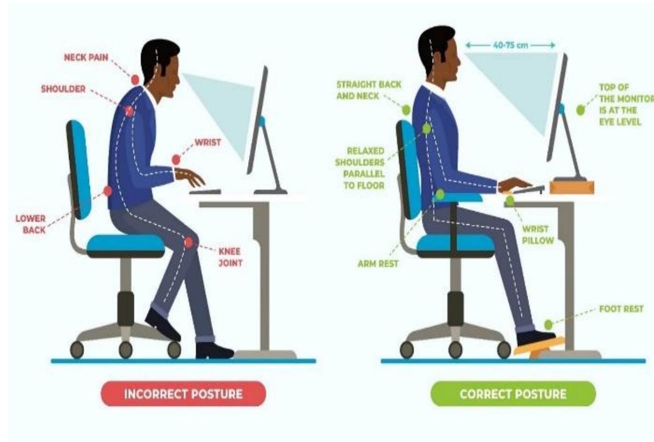

Fig. 2 Ergonomic posture levels

It also makes it possible to assess the relative discomfort associated with a work position, considering the arrangement of the back, arms and legs, along with the required load levels (Figure 2). Through the assignment of a score, the system indicates the importance of implementing corrective measures to mitigate the discomfort associated with such a job position [28].

2.2. Ergonomics and Artificial Intelligence

Implementing physical ergonomics proves to be an effective approach for monitoring potential work-related disorders. In this context, technologies with promising prospects are emerging in terms of diagnosis, prognosis and prevention. These include physical sensors like the accelerometer, gyroscope and biopotential sensors (EMG, EEG, EKG/ECG). These innovations play a crucial role in identifying and categorizing workers' postural and biomechanical loads, enabling the creation of algorithms applicable in the field of musculoskeletal disorders [9].

The presence of sensors that contribute to adequate processing of information for the purpose of diagnosing, prognosis, or preventing musculoskeletal injuries stands out as a transcendental aspect where artificial intelligence is already deploying its efforts for the benefit of workers' working conditions [29-31]. It is important to note that, among the professionals engaged in various activities within the field of engineering, there are elderly people. Within this framework, artificial intelligence-assisted orthopaedic devices have been developed to improve the mobility of the lower extremities [32]. This approach represents a new design standard to address workplace mobility challenges. Artificial intelligence can potentially elevate worker performance by improving routine tasks and optimizing focus time at work. This aspect is critical for improving job performance, training, professional management, and disease reduction [33]. On the other hand, human factors and ergonomic principles [34] linked to artificial intelligence in the field of health play a key role in improving situational awareness in the workplace (see Table 1).

Table 1. Ergonomics principles and human factors applied to artificial intelligence in the field of occupational health

Human Factors	Ergonomic Principles
Knowledge of Reality	Analyzing how artificial intelligence affects workload is essential, as it can decrease or increase workload in certain contexts.
Workload	It is imperative to explore strategies that prevent blind trust in artificial intelligence, such as implementing detailed explanations and training programs.
Automation Trend	It is necessary to evaluate approaches impeding trust in artificial intelligence, such as providing explanations and conducting training programs.
Description & Reliability	It is critical that AI applications communicate and make it easier for users to review how they work, to mitigate potential automation biases and strengthen trust.
AI Human-Machine Collaboration	It is essential for AI applications to demonstrate effective collaboration, foster shared mental models and promote situational awareness for optimal team performance.
Learning	When introducing artificial intelligence, it is crucial to provide people with opportunities to exercise and maintain their skills and ensure that they possess a fundamental understanding of how AI works. The focus should be on designing accessible and flexible training programs, providing protected time during working hours for staff to undertake such training.
Interpersonal Communication	The effect on relationships, such as the ability for staff to work remotely, should be considered as artificial intelligence becomes more widely integrated.
Ethical Principles	In the healthcare sector, artificial intelligence poses ethical challenges related to fairness and bias in models, privacy protection, respect for autonomy, profit maximization, and risk reduction.

There are artificial intelligence systems such as RGB and 3D sensors that can acquire information about the operator's condition, the surrounding environment, and process progress using Machine Learning (ML). These systems offer personalized assistance to the operator using collaborative robots (Cobots) to carry out shared tasks, automatically adjusting to the operator's needs (Figure 3). They are also capable of modifying the robot's posture to improve ergonomics, using algorithms based on heuristic searches [35-37]. Collaborative robots not only improve the work environment by reducing injuries in certain activities but also assist in the constant evolution of artificial intelligence. This evolution constantly brings new technologies and techniques that build trust among users, given their significant impact on virtually every industry and people's lives [38].

Fig. 3 Cobot working environment

Extensive research has also explored the interconnectedness between artificial intelligence, human security, and mental health [39-41], mentions that artificial intelligence implies the ability of machines to learn and reason in ways analogous to human beings, playing an increasingly crucial role in various applications, from robot management to strategies in games such as chess.

On the other hand, human security encompasses the protection of people from violence and various threats, addressing a wide range of areas, such as economic, health, food, and environmental security. It can be said that integrating artificial intelligence into ergonomics offers the possibility of creating more personalized solutions tailored to individual needs. Intelligent systems can analyze biometric data and behavioral patterns to dynamically adjust environments and devices, improving both user comfort and productivity.

2.3. Ergonomics and Digital Twins

In the era of Industry 4.0, digital twins play an important role in modeling and integrating valuable information from production systems [42]. These digital twins facilitate the acquisition and exchange of data [43], enabling the creation of virtual reproductions of products, processes, and manufacturing media in a visual interface [44]. A digital twin represents a physical reality that provides essential decision-making elements [45]. This approach helps optimize business performance [46] through an architecture that stores current state and historical data. In addition, it incorporates elements of data capture, information management, and real-time model update tools [47]. Digital twins find applications in various fields, such as the analysis of health conditions for the planning of maintenance activities, the management of the life cycle of physical objects, and the improvement of decision-making through engineering and numerical analysis [47]. Ergonomics, which focuses on the psychophysical and social well-being of workers [48], acquires special relevance in scenarios such as Human-Robot Collaboration (HRC). In this context, digital twins make it possible to plan, simulate, monitor, and optimize the interaction between humans and robots [49, 50]. Cognitive ergonomics becomes essential in collaborative environments, where the design of the workspace must reduce the physical and mental load of the human operator. In the field of Industry 4.0 production, digital twins are crucial elements for process ergonomics. These facilitate real-time tracking of manual work activities, helping to prevent risk factors in manufacturing environments. [51] propose a methodology that uses digital twins to assess ergonomic risk at workstations, reducing calculation times and data analysis.

This approach is essential to avoid injuries or musculoskeletal alterations caused by awkward postures and repetitive actions. In the realm of production, technologies that add to the use of digital twins include Virtual Reality and Augmented Reality, playing a crucial role in optimizing ergonomics, implementing safety policies, and efficiently assigning tasks, among other applications [31]. In the evolution towards Industry 5.0, conceived as an industrial revolution focused on core values such as human well-being, sustainability, flexibility, and efficiency [52], automation is redefined as the incorporation of human creativity, objective thinking, dexterity, and decision-making using robots, especially in tasks that are dangerous for employees [53]. In this context, digital twins play a crucial role in being applied in monitoring, evaluation, and optimization to improve human performance, ergonomics, and overall well-being [54].

2.4. Ergonomics and Exoskeletons

Work in an industry often involves activities that involve stress on the body. These activities mainly involve carrying loads over the head, adopting forced postures such as squatting, and performing repetitive movements, which affects response and physical endurance as a function of execution time. The introduction of exoskeletons has brought workers substantial benefits and physical improvements. These devices enable workers to maintain specific positions with minimal muscular effort, thereby decreasing the risk of injuries and musculoskeletal disorders. Occupational Exoskeletons (EXOs) have emerged as an effective solution for reducing fatigue and physical strain associated with various job tasks. They are now widely implemented in manufacturing processes, assembly lines, and multiple industrial sectors [55-58]. Exoskeletons (Figure 4) are devices designed to provide strength and endurance, protecting the operator from the negative effects associated with heavy labor tasks [59-61]. Integrating smart glasses and augmented reality projectors enhances this technology by facilitating the execution of activities more flexibly through access to information and virtualization [62].

Fig. 4 Example of exoskeletons

These types of devices are an effective means by which robots collaborate with humans, avoiding the risk of injury. These portable structures support the worker's muscles and skeletal system during demanding physical tasks. In this way, technology 4.0 contributes significantly to optimizing operators' working conditions, generating a work environment with a socially sustainable approach [63, 64].

Exoskeletons have proven valuable in optimizing performance in efficiency and effectiveness, especially in tasks involving material handling, such as picking up, carrying, and lifting heavy objects. In addition to generating economic advantages, they have also contributed to improving the social protection of workers [65-67].

In addition, they are characterized by the incorporation of actuators, which are mechanical components responsible for enhancing human strength. To achieve optimal performance, these devices need to receive external energy and have elastic elements that allow them to store and release energy during movement [68-71].

On the other hand, exoskeletons in manufacturing offer several advantages that can improve efficiency, safety, and quality of work. Here are some of the most important advantages (see Table 2).

The combination of ergonomics and exoskeletons can prove especially powerful when integrating ergonomics into the design of exoskeletons, as they can create more effective and comfortable solutions that optimally fit the user's needs. This leads to significant improvements in labor productivity, workplace safety, and the prevention of work-related injuries.

Table 2. Advantages that can improve efficiency, safety and quality at work

Advantages	Description
Increased Strength and Endurance	They allow workers to perform tasks that require additional physical strength without experiencing excessive fatigue. This can lead to increased productivity and reduce the risk of workload-related injuries.
Improved Ergonomics	They are designed to improve posture and reduce stress on muscles and joints. This can help prevent musculoskeletal injuries and improve worker comfort during long workdays.
Reduced Injury and Fatigue	They can reduce the risk of injuries to the back, shoulders, and other body areas. They also help mitigate fatigue, especially in jobs requiring repetitive motions or heavy lifting.
Increased Accuracy	They provide greater precision in delicate movements, which is valuable in manufacturing environments that require precise work.
Improved Security	By making it easier to handle heavy loads and alleviating fatigue, exoskeletons can contribute to a safer work environment by reducing the likelihood of workload-related accidents and injuries.
Adaptability and Customization	They are typically adjustable and adaptable to different body sizes and shapes, allowing workers to customize their equipment to meet their specific needs.
Facilitation of Rapid Training	Using ergonomically designed exoskeletons allows workers to adapt more quickly to new tasks or production processes, which is beneficial in manufacturing environments requiring flexibility and frequent change.
Reduction of Absenteeism from Work	They can contribute to decreased absenteeism from work due to work-related injuries.
Automation Support	It can be integrated with automation systems to improve efficiency and collaboration between humans and robots.

3. Materials and Methods

The study adopts a systematic literature review approach to identify and analyze relevant research on the impact of virtual reality, artificial intelligence, digital twins, and exoskeletons on ergonomics, with the aim of understanding their contribution to the transition to technological ergonomics 4.0. It examines how these technologies have benefited both workers and companies in the context of Industry 4.0. To ensure rigor and accuracy, a structured procedure was followed, including literature search, data extraction and information synthesis, details of which are presented in the following sections. The research team, composed of five specialists based in Mexico, defined the search terms, key definitions and scope of the study from the beginning of the process. The literature search focused on empirical studies published in international peer-reviewed journals, covering qualitative, quantitative and mixed-methods approaches.

Research on the relationship between ergonomics and emerging technologies such as virtual reality and artificial intelligence was analyzed, as well as other innovations applied to the optimization of ergonomic conditions in production processes. This analysis is part of the evolution of Industry 4.0 and its impact on ergonomics, with a view to a more efficient future adapted to the needs of workers and companies. The search was initiated using the following four strings.

- String 1: Virtual reality, continuous improvement, Industry 4.0, Cobots.
- String 2: EMG, EEG, Optimization, Efficiency, Decision-Making, Industry 4.0.
- String 3: Human-machine interaction, resilience, sustainability, quality ethics, sustainable manufacturing learning.
- String 4: Ergonomics 4.0, digital twins, Productivity, Competitiveness, Performance, OWAS, AI.

However, only 12 studies that met the established criteria were obtained. To verify and ensure the integrity of the search, advanced search algorithms were implemented in three databases:

Ebsco Essential, Scopus, MDPI, Emerald Insight, and Taylor & Francis. These algorithms were systematically applied across databases, using appropriate truncations and Boolean operators, such as AND and OR, to optimize the retrieval of relevant studies (Table 3).

This study focuses on examining the positive impact that some 4.0 technologies have had on companies, improving both their productivity and the health and safety of their workers. It began with a search that yielded more than 639 titles and abstracts describing the results of applications that involve the interaction of various study elements through previously mentioned electronic databases.

After removing 45 duplicates, 594 papers were obtained. Of these, 165 were excluded because they did not meet the objectives of the research, 55 because they did not fit the target population, 143 because they did not present applications in engineering areas, and 171 because they were not relevant in terms of the information provided.

Table 3. Search algorithms for extracting documents from databases

Database	Search Algorithms
EBSCO-Essential	AND virtual reality Title AND ergonomic Abstract AND industry 4.0 Keyword
	AND artificial intelligence Title AND ergonomic AllFields AND industry 4.0 Subject
	AND digital twins Keyword AND ergonomic Keyword AND industry 4.0 Subject
	AND exoskeletons Title AND ergonomic Keyword AND industry 4.0 Keyword
MDPI	Virtual reality (title) AND ergonomic (abstract) AND ergonomic (Full text) AND industry 4.0 (Full text)
	Artificial intelligence (title) AND ergonomic (abstract) AND ergonomic (Full text) AND industry 4.0 (Full text)
	AND digital twins Title AND ergonomic Keyword AND industry 4.0 Subject
	AND exoskeletons Title AND ergonomic Keyword AND industry 4.0 Keyword
Emerald Insight	(content-type:article) AND (title:"virtual reality" AND (ergonomic) AND (industry 4.0))
	(content-type:article) AND (title:"artificial intelligence" AND (ergonomic) AND (industry 4.0))
	(content-type:article) AND (title:"digital twins" AND (ergonomic) AND (industry 4.0))
	(content-type:article) AND (title:"exoskeletons" AND (ergonomic) AND (industry 4.0))
Taylor & Francis	Title (virtual reality) AND Abstract (ergonomic) AND Anywhere (industry 4.0)
	Title (artificial intelligence) AND Anywhere (ergonomic) AND Anywhere (industry 4.0)
	Title (digital twins) AND Anywhere (ergonomic) AND Anywhere (industry 4.0)
	Title (digital twins) AND Anywhere (ergonomic) AND Anywhere (industry 4.0)

To ensure that the information is up-to-date, priority was given to the inclusion of research published in the last 15 years, thus offering an up-to-date perspective, especially about the use of new technologies in ergonomics and the adoption of Industry 4.0. As a result, the adequacy and inclusion of the full texts of 60 studies in this systematic review were evaluated. The PRISMA flowchart model was used to present information [72]. (Figure 5).

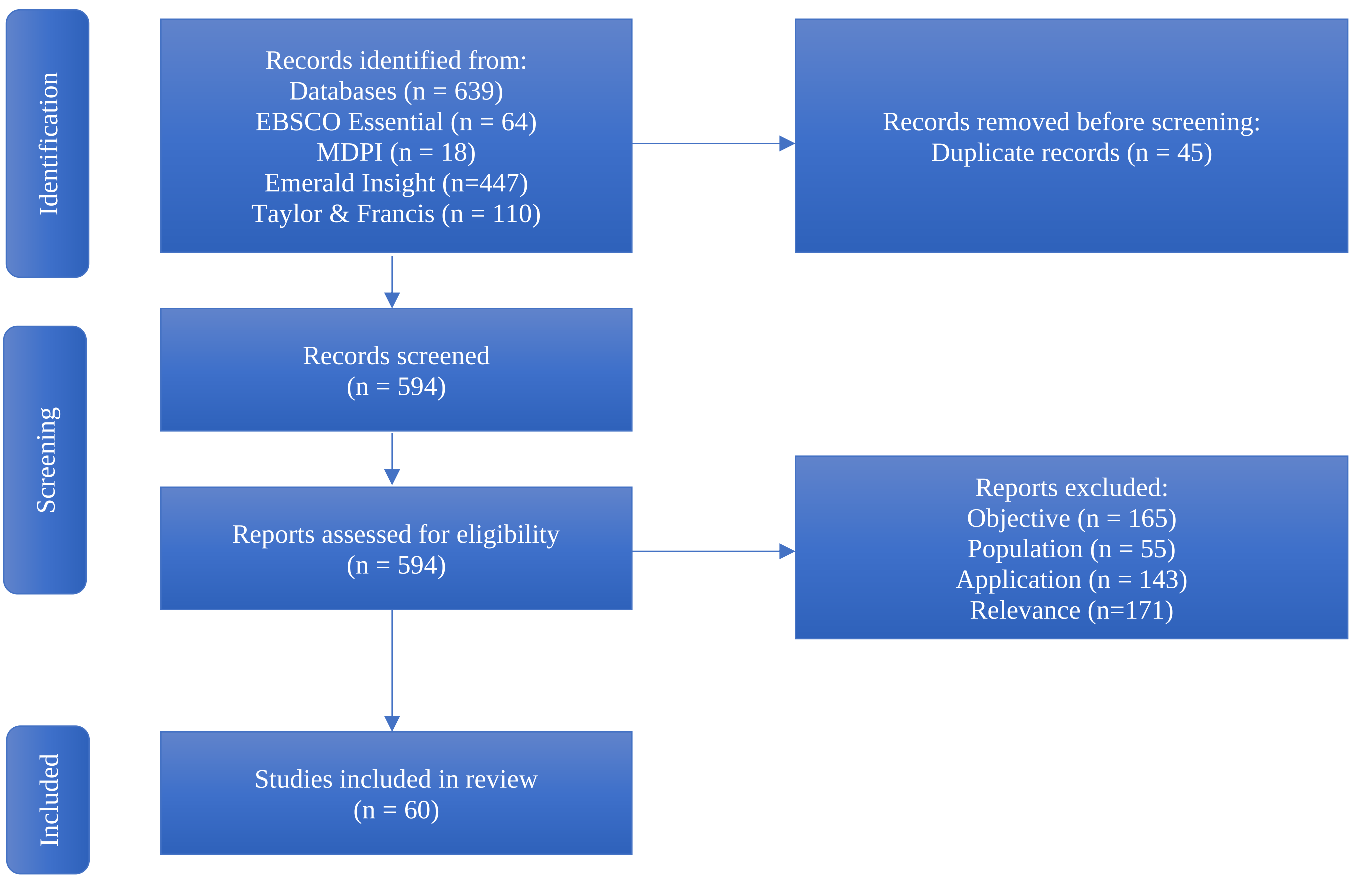

Fig. 5 Presentation of information with PRISMA flowchart

Table 4 details the search mechanism used to obtain information with the following data: name of the main author, method used in research, study objective, and results or findings. The recently adopted literature search was conducted in databases such as EBSCO Essential, MDPI, Emerald Insight, and Taylor & Francis, using Vosviewer software. The analysis is based on the bibliometrics of the literature, although this is not the case for this work. However, the principle of the Word Cloud worked with the MAXQDA analysis software used. The bibliographic search is frequently used in the so-called state-of-the-art of researchers who seek the theoretical foundations of their study variables. The database matrix built with the existing literature is presented below.

4. Results

4.1. Summary of Results

Table 4 describes the main characteristics of the 60 articles identified through a systematic search, classified according to research methods, objectives and findings. Regarding the review of the literature focused on ergonomics (30 articles), the use of exoskeletons and 4.0 technology applied in the work environment and production systems stands out. In terms of analysis of processes and practices (5 articles). In the field of prototype design, systems based on sensors and algorithms (7 articles), technologies such as the Digital Twin (DT) and virtual reality were addressed. Finally, the analysis of the workers' environment and specific body analysis is needed (18 articles).

Table 4. Search mechanisms

Authors	Method	Objective of the Study	Outcome Measures in the Study
Naranjo, J.	Literature review	Preservation of the integrity of workers	Job Training Efficiency
Herrera, D.	System for virtual welding process training	Virtual Skill Manipulation	Virtual Skill Manipulation
García, C.	Development of a Virtual Training System	Virtual Skill Manipulation	Virtual Skill Manipulation
Di Pasquale, V.	Literature review	Knowledge Across Workforce and Virtual Technologies	Applications of VR in Manufacturing Systems
Uyar, A.	Literature review	Virtual Ad Recovery Test Comparison	Benefits of Virtual Reality
De Freitas, F.	Literature review	Knowledge of VR applications	Challenges, benefits and contrasts
Otto, M.	Literature review	Performance Applicability Assessment	EAWS Work Postures
Adwernat, O.	Design Review for VR-Based CPS	Design Review	Validation of the existing VR concept
Kačerová, I.	Analysis of preliminary results	Analysis of the influence of EMG activity position	EMG Influence
Otto, M.	Holistic framework and performance analysis using algorithms	In-depth precision analysis and sensor fusion	Performance of conventional systems
Kačerová, I.	Ergonomic design	Ergonomic Workstation Design	Potential Problems
Gonçalves, A.	Patent and literature review	VR Application Analysis and Human Modeling	Novel solutions for detecting ergonomic problems
Peruzzini, M.	Comparative study	Physical workload analysis	Workstation Design
Oyekan, J.	Comparative Research	Secure Implementation of Cobot Strategies	Strategies
Reinhard, R.	Identifying potential problems	Event-Based Instruction Sampling	VR Usage Challenges
Donisi, L.	Systematic review of the literature	Analytics through artificial intelligence	Diagnostic Insights
Svertoka, E.	Survey	Ensuring occupational safety	Challenges of Wearable Devices
Chidambaram, S.	Artificial intelligence detection/narrative review	Data collection	AI Challenge Solving Solutions
Nahavandi, S.	Literature review	Challenge analysis	Impact of Industry 5.0
Yu, Z.	Perspective Engineering Design	Analysis of advantages and disadvantages of movements	Lower Extremity Design Validation
Lin, S.	Exploratory Research	Impact of abusive management of human interaction technologies	Human-machine interface

Sujan, M.	Human Factors Analysis	Scope of AI in Healthcare	Performance of the sociotechnical system
Dimitropoulos, N.	Automatic System Proposal	Ergonomic evaluation	Collaboration Efficiency
Papakostas, N.	Literature review	Discussion of the literature	Industry 4.0 principles
Wang, X.	Classification Framework	Definition of terminus	Packaging System
Szymoniak, S.	Comprehensive Review of Artificial Intelligence Methods	Reliability analysis of techniques	AI Solutions
Prasad, K.	Literature review	Provide a comprehensive review and analysis of the interaction between artificial intelligence (AI) and psychology.	Features and Overview
Lieto, A.	Cognitive search	Knowledge of AI systems	AI Principles
Ahmed, N.	Analysis of practices	Understanding Threats	Identifying Potential AI Threats
Hernández, Y.	Case Study	Obtaining a simulation model	Resource Utilization Decision-Making
Liu, M.	Literature review	Digital twin status analysis	Key technologies and future directions
Aquino, J.	Literature review	Relevance of 4.0 technologies	Frontier Demonstration
Varas, M.	Literature review	Literature review	Recent developments
Parrot, A.	Concept Paper	Industry 4.0 Definition and Digital Twins	Definition and advantages of digital twins
De Prada, C.	Literature review	Study of benefits and challenges	Prototype Challenges and Difficulties
Kritzinger, W.	Impact of Additive Manufacturing	Impact of Additive Manufacturing	Relationships and challenges
Gualtieri, L.	Systematic review of the literature	Analysis of occupational safety and ergonomics	Further development in security issues
Baratta, A.	Literature review	DTS Trends and Applications	Data Exchange Capabilities
Wang, S.	Digital Frame	Object detection with convolutional network	System validation and evaluation
Greco, A.	Proposed methodological framework	Implementation of digital human twin	Identifying operational issues
Xu, Z.	Concepts and perceptions	Situation of Industry 4.0	Discussions
Land, N.	Framework of reference	Main Step Development Process	Comprehensive framework
Löcklin, A.	App Review	Interface Development	Adaptation of conventional architectures
Schwerha, D.	Focus groups	Benefits related to job tasks	Concerns, costs, and working conditions
Ricco, M.	Online Survey	Survey for the analysis of exoskeletons	Real characteristics of exoskeletons
Deshpande, N.	Literature review	Current Development Status of Exoskeletons	Analysis of future applications
Zelik, K.	Ergonomic Assessment Tool	Risk Assessment Tool	Effects prediction benefits of expos
Shanmukha, Y.	Exoskeletal Technology Applications	Use of chitosan for processing outcomes	Exoskeleton vents with chitosan technology
Da Silva, R.	Operational analysis	Evaluation of Musculoskeletal Disorders	Machine Learning Analytics
Unda, O.	Literature review	Exoskeleton analysis occupational health	Development and innovative technologies
Romero, D.	Literature review	Resilience of operators at work	Adequate resilience levels
Cimini, C.	Logistics Advancements in the Supply Chain	Knowledge of Industry 4.0 applications	Benefits of I4.0 in the supply chain

Ferraro, S.	Study and review of the literature	Benefits of Logistics 4.0	Identification of technologies
Montmans, R.	Literature review	Posture Exoskeleton Effects	Prevention practices
Wei, W.	Prototype Design	Exoskeleton design	Exoskeleton
Van, R.	Fatigue reduction method	Exoskeleton design	Exoskeletons
Dempsey, P.	Exploratory Research	Emerging opportunities	Ergonomic opportunities and advantages
Sorlini, A.	Trends & Stories/Literature Review	Improvements in occupational safety and health	Dissemination of culture and safety
Botti, L.	Literature review	Worker Analysis	Impact of exoskeletons on workers
Shafaei, M.	Literature review	Operational analysis	Discussions

4.1. Analysis of Information

The 2020 version of the MAXQDA software was used in the qualitative analysis. Its word cloud generation function made it possible to visualize a set of words from the text in a structured way, organizing the terms in a hierarchical way according to their frequency. Figure 6 shows the most recurrent keywords used to search for information from the scientific literature applied in this study.

Fig. 6 Most frequent keywords using word cloud

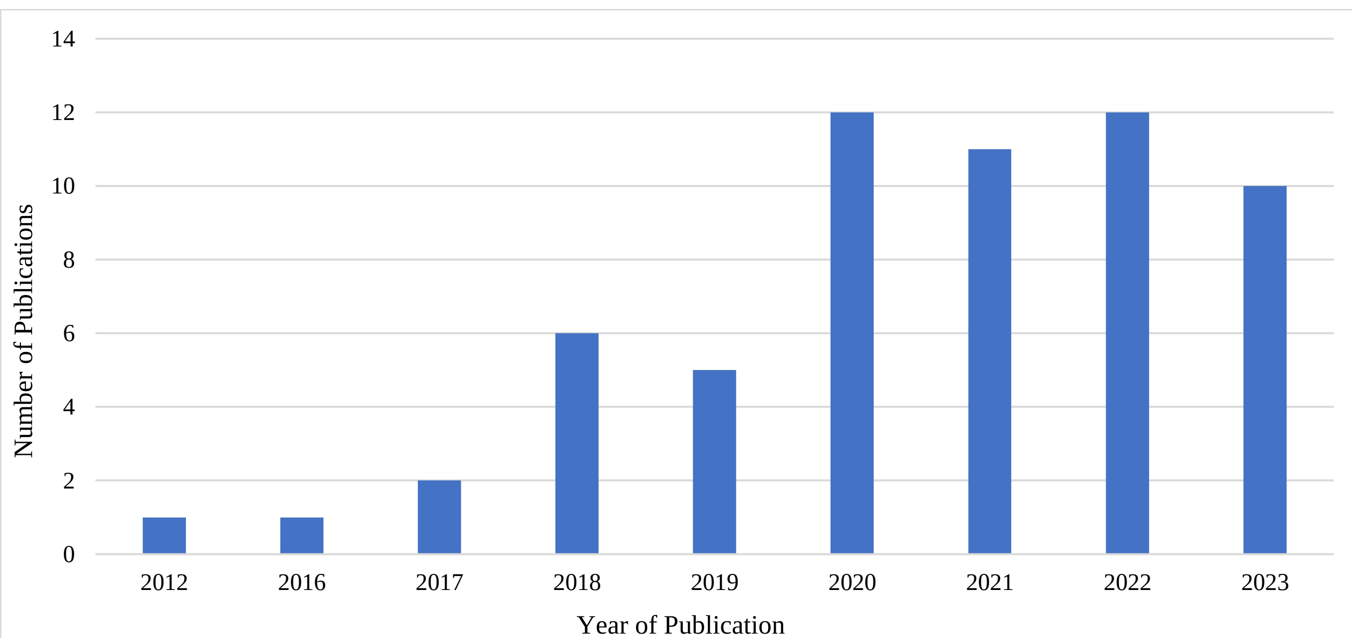

Fig. 7 Number of publications per year

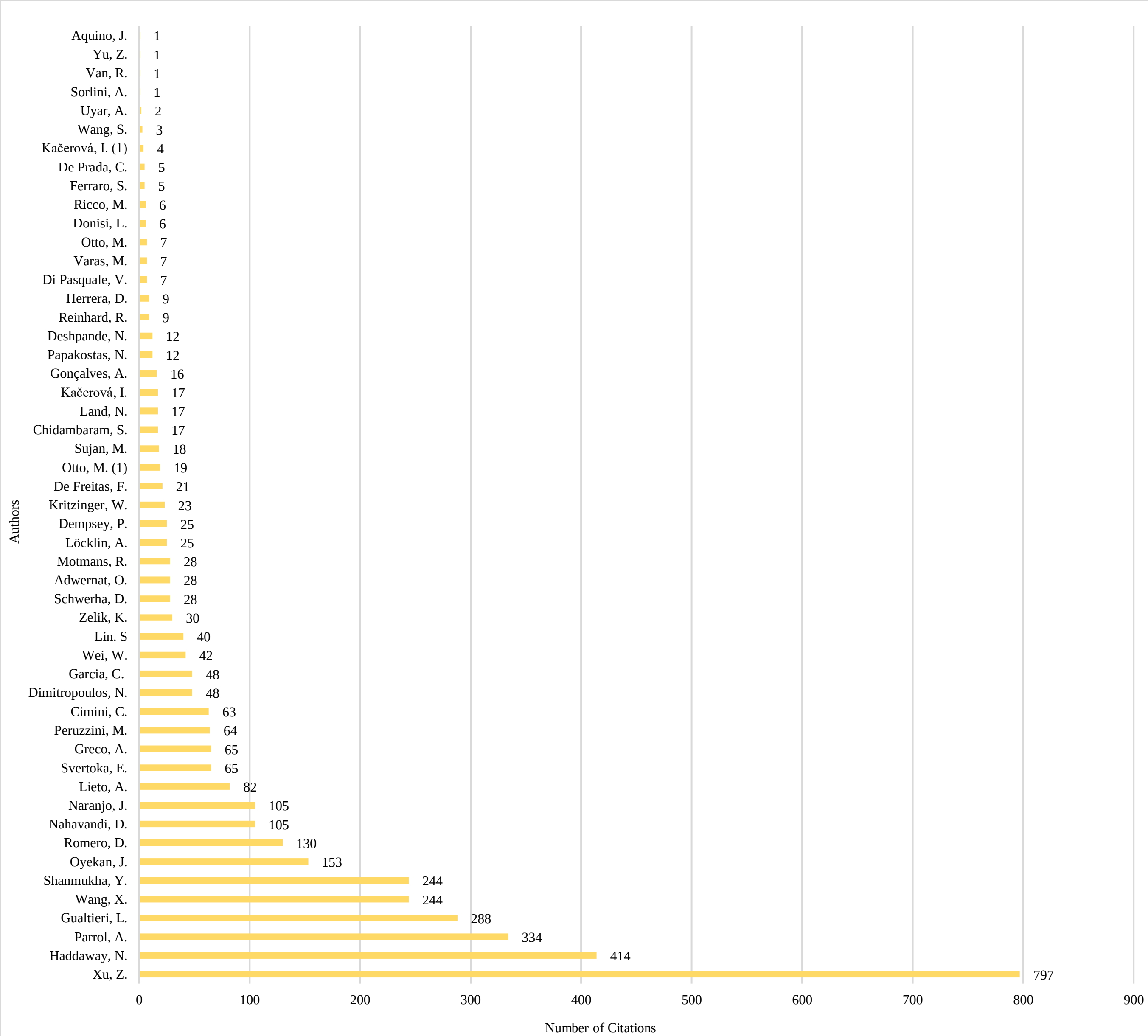

Fig. 8 Number of citations per author

In the publications related to the research topic, it was determined that 75% of the total research is located between the years 2020 and 2023, which means that it is one of the innovative topics for the benefit of ergonomics and that it is being implemented as part of 4.0 technologies in organizations. The average distance from observations to the centroid of the cluster of the observations within each cluster is also shown (Figure 7). Below is the corresponding number of citations per author, according to the literature used to analyse the information. Citation results were obtained using the Google Scholar citation browser (Figure 8). The results show 3 works with a high level of mentions. The first work corresponds to the author Liu in 2020, who presents a total of 896 citations, where the author made a review of concepts and technologies related to digital twins. In second place is the author Nahavandi, who in 2019 developed research on Industry 5.0 as a hub for human solutions. Finally, in third place is author Haddaway 2020, who developed an R-language-based package called PRISMA2020 to produce interactive flowcharts for optimized digital transparency and open synthesis.

5. Conclusion and Future Directions

Integrating Industry 4.0 into ergonomics represents a significant leap towards more efficient work environments tailored to the individual needs of workers. Emerging technologies such as augmented reality and automation improve work experience and identify and reduce ergonomic risks in real-time, decreasing workplace injuries. The interconnection between machines and people in smart environments not only optimizes operational efficiency but also enables the customization of work environments, creating healthier and more productive spaces. Real-time data collection and analysis offer valuable insights for continuous improvements, boosting ergonomic and operational aspects. When it comes to workplace ergonomics, Industry 4.0 offers both challenges and opportunities. Automation and the use of robots can reduce the physical load and risk of injury in repetitive and dangerous tasks, thereby improving the health and well-being of workers. However, introducing new technologies also requires adaptation in the design of jobs and in the training of employees to avoid problems related to human-machine interaction and technological stress. Although the transition to Industry 4.0 requires developing digital skills, it represents an opportunity for professional growth and adaptation to technological evolution. However, it is crucial to address the ethical and private concerns associated with implementing advanced technologies in the workplace and establish strong regulatory frameworks to protect workers' rights. While the integration of Industry 4.0 into ergonomics offers multiple benefits, there are still areas that require further exploration. Future research could focus on assessing the long-term impact of the use of technologies such as artificial intelligence and augmented reality on workers' health, as well as on adapting different industrial sectors to these innovations. In addition, it is necessary to deepen the development of predictive models that allow ergonomic risks to be anticipated more accurately. Among the main limitations of this study is the lack of longitudinal data on the effects of automation on ergonomics and the need to establish stronger regulatory frameworks that balance technological implementation with the protection of labor rights. These challenges open up new opportunities for research at the intersection of ergonomics, technology, and work ethics.

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