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ERGONOMICS/HUMAN FACTORS IN THE ERA OF SMART AND SUSTAINABLE INDUSTRY: INDUSTRY 4.0/5.0

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Abstract:
The three primary branches of ergonomics/human factors (E/HF), concentrate on the physical, cognitive, and organizational dimensions, have developed over time. Generally, E/HF is the scientific discipline concerned with the design and arrangement of work environments, systems, and products to fit the physical, cognitive, and emotional needs of the people who use them. The goal of E/HF is to optimize human well-being and overall system performance by improving comfort, safety, efficiency, and productivity while reducing the risk of injury and strain. E/HF is increasingly relevant in the context of Industry 4.0 characterized by automation, cyber-physical systems, and interconnected technologies. The integration of advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, and augmented reality (AR) within manufacturing environments presents both opportunities and challenges for worker well-being. Development of industrial technologies requires also a rethinking of traditional E/HF principles to address new human-machine interactions, cognitive demands, and the physical layout of workplaces. E/HF benefits and the threats of Industry 4.0/5.0 technologies must be considered in an integrated manner. The importance of designing systems that promote user-friendly interfaces, reduce mental and physical strain, and support sustainable work environments now becomes critical. In this context, this review paper explores the connection between E/HF and Industry 4.0/5.0, emphasizing the need for a holistic approach to designing work systems that enhance both human performance and technological innovation.

Key words: safety work, ergonomics (E/HF), cognitive ergonomics, Industry 4.0/5.0

INTRODUCTION

The rapid technological advancements ushered in by Industry 4.0 have redefined workplaces, transforming how humans interact with machines, systems, and data. This era, characterized by smart factories, interconnected devices, and automation, has brought significant productivity gains but also introduced new challenges to the physical and cognitive well-being of workers. In this intricate technology-driven work, ergonomics/human factors (E/HF) has emerged as a vital field focused on enhancing human performance and comfort. Traditionally, E/HF focused on designing tools, workspaces, and systems to minimize physical strain and maximize efficiency. However, in the context of Industry 4.0 the discipline has evolved to address a broader range of factors, including human-machine interaction, cognitive load, and the integration of digital tools [1, 2, 3]. As industrial systems grow smarter, E/HF must account for the dynamic interplay between human workers and advanced technologies like artificial intelligence (AI), robotics, and the Internet of Things (IoT). The convergence of E/HF and Industry 4.0 also brings a unique opportunity to leverage data and emerging technologies to create human-centric workplaces. By using wearable devices, augmented reality (AR), and predictive analytics, organizations can not only enhance worker comfort but also proactively identify risks and improve overall system performance. This synergy ensures that technological progress aligns with the well-being of the workforce, fostering sustainable and innovative work environments.

This article explores the evolution of E/HF within the context of Industry 4.0 and beyond. It explores the evolution of E/HF from its origins to its current state, highlighting how it has adapted to meet the demands of modern industrial environments. Moreover, it examines the potential for E/HF innovations to shape future workplaces, where technology and humanity coexist harmoniously.

E/HF BEFORE INDUSTRY 4.0: HISTORICAL VIEW

E/HF, the study of designing work environments, systems, and tools that enhance human well-being and efficiency, has a long and rich history. From its roots in the industrial age to its evolution in modern workplaces, E/HF has continually adapted to meet the changing demands of society, especially as technology advanced over time. Before the era of Industry 4.0 E/HF was primarily focused on minimizing physical strain, optimizing task efficiency, and improving safety within industrial settings (physical ergonomics). However, as industries advanced, the scope and methodologies of E/HF evolved as well.

Early developments in E/HF

The origins of E/HF can be traced back to the early 20th century. During this time, factories and manual labor became more prevalent, and so did the need to address the challenges posed by repetitive tasks, poor workspaces, and unsafe working conditions. Early proponents of the concepts from which E/HF emerged, such as Frederick Winslow Taylor and Frank and Lillian Gilbreth, included concepts aimed at improving productivity through task optimization and reducing physical strain [4]. Taylorism, or "scientific management," became one of the first systematic approaches that can trace its way to industrial ergonomics. Taylor"s principles focused on analyzing and streamlining work processes to enhance efficiency, which often involved breaking down tasks into smaller, more manageable parts [5, 6, 7, 8, 9, 10]. However, these early approaches primarily prioritized efficiency over worker well-being, often leading to negative consequences like fatigue and physical discomfort [11]. Meanwhile, the Gilbreths, who studied time and motion, emphasized the importance of reducing unnecessary movement and designing tools that facilitated smoother and more natural workflows. Their work highlighted the importance of designing tasks that minimized physical strain, laying the foundation for the concept of "human-centered design" [12].

The shift towards safety and wellbeing

As industrial practices advanced and automation became more prevalent, E/HF began shifting focus toward improving worker safety and well-being. The rise of occupational health and safety regulations in the mid-20th century marked a turning point for E/HF. In this period, companies started addressing workplace risks by designing safer machinery, ensuring proper workstation layouts, and creating environments that reduced physical hazards. During the 1950s and 1960s, the field expanded beyond physical ergonomics to encompass mental and cognitive well-being [4, 13, 14, 15, 16]. Human factors psychology emerged, focusing on how psychological factors, such as attention, stress, and cognitive load, affect workers" ability to perform tasks effectively. This shift introduced concepts such as user-friendly interfaces, reducing cognitive load, and designing workplaces that accommodate diverse human capabilities.

E/HF in the automation era

As automation and technology progressed in the mid-20th century, E/HF adapted to meet the challenges posed by automated systems. Work environments became increasingly digital, introducing computer-based tasks, user interfaces, and collaborative systems. The focus shifted toward human-computer interaction (HCI), ensuring that these systems were intuitive, reducing the cognitive burden, and allowing operators to interact efficiently with complex technologies [17, 18, 19]. During this period, E/HF research also delved into physical and psychological aspects of workstation design, including issues such as repetitive strain injuries (RSIs) and mental fatigue. Innovations like adjustable desks, ergonomic seating, and anti-fatigue flooring were developed to provide greater comfort and reduce long-term health risks.

Internal lessons from the history of E/HF

Throughout its history, E/HF has evolved through a series of technological advancements and societal changes. From the industrial revolution to the era of automation and beyond, the field has consistently sought to create more balanced and efficient work environments. However, it wasn"t until the integration of digital technologies that E/HF truly began to address more nuanced challenges, such as cognitive ergonomics and human-machine collaboration [19, 20, 21, 22, 23, 24]. As we look back at the historical perspective of E/HF, it is clear that the discipline has always strived to adapt to new realities. The transition from manual labor to automation, and now to the interconnected smart factories of Industry 4.0 reflects the continued evolution of E/HF principles to better serve workers in increasingly complex technological landscapes [25].

E/HF IN THE AGE OF INDUSTRY 4.0

The dawn of Industry 4.0 has transformed the way businesses operate, introducing advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), robotics, and data-driven decision-making into industrial environments. As these technologies converge, the workplace becomes increasingly connected, automated, and optimized for efficiency. However, this evolution also brings unique E/HF challenges, requiring a rethinking of how human workers interact with machines and digital systems. E/HF in the age of Industry 4.0 must balance technological advancement with human well-being to create sustainable, safe, and efficient workspaces [26]. One of the most significant aspects of E/HF in

Industry 4.0 is the interaction between humans and machines. As automation becomes more prevalent, the focus shifts toward ensuring that these interactions are intuitive and minimize physical and cognitive strain. Human-machine interaction (HMI) design must account for how workers perceive, process, and control complex systems within an increasingly digital landscape [27, 28]. For example, user-friendly interfaces, real-time feedback, and adaptive technologies can reduce cognitive overload, making tasks more manageable and efficient. With the integration of AI and machine learning, systems can now predict user needs and adapt to them in real-time, enhancing the human-machine collaboration. However, this also creates challenges related to data security, privacy, and maintaining a balanced workload. E/HF design in this context ensures that these interactions are fluid and safe while protecting worker well-being [29, 30]. Now, a new name and concept of E/HF for Industry 4.0 era is established – cybergonomics, and a new research road map is proposed for this new subdiscipline of E/HF [31]. Cybergonomics is a new word composed of prefix "cyber" and word "ergonomics". In a broader definition, cybergonomics is the study of human performance in interaction with cyber-technologies to optimize individuals" safety, productivity, and health. In other words, the study of the benefits and challenges of emerging technologies in the Industry 4.0 to adapt these technologies to humans" capabilities and physical, mental, and spiritual limitations in the living and working environment will be within the scope of cybergonomics.

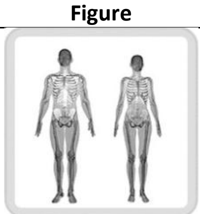
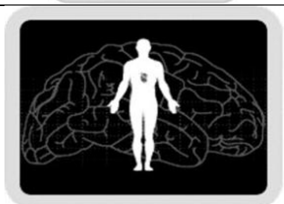
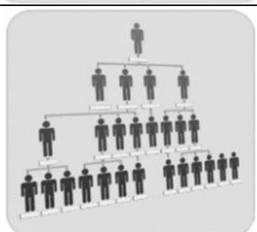
In smart factories, where automation drives productivity, E/HF design must address the physical and psychological impacts of automation. Assembly lines that once relied on manual labor are increasingly populated by robotic arms, automated vehicles, and self-driving systems. These advancements reduce repetitive tasks and physical strain but present new challenges in ergonomically accommodating human oversight, troubleshooting, and maintenance. Workers who interface with these automated systems face challenges such as adjusting to rapidly changing technologies, navigating between manual and automated tasks, and maintaining focus amid a highly interconnected environment. E/HF solutions in this context include designing comfortable, flexible workstations, incorporating adjustable settings for different task requirements, and developing methods to limit eye strain and physical discomfort.

Cognitive ergonomics in a digital age

Beyond physical ergonomics, cognitive ergonomics plays an essential role in the age of Industry 4.0. Cognitive ergonomics refers to the study and application of designing work systems, tools, and environments that optimize mental processes and reduce cognitive load, with the goal of improving overall performance, safety, and well-being [32, 33, 34]. It focuses on understanding how people perceive, process, and interact with information, making sure that tasks, technologies, and environments are aligned with human cognitive capabilities and limitations (Table 1).

Cognitive ergonomics aims to minimize errors, manage mental workload, and enhance decision-making by creating intuitive and user-friendly systems that support efficient and effective task execution [34]. As work increasingly involves managing data, making decisions based on artificial intelligence outputs, and interacting with complex digital systems, the mental workload of workers rises significantly. This shift necessitates uniqueness needs to understanding how cognitive processes impact performance and well-being.

Table 1
Three dimensions of ergonomics

Type of ergonomics	Figure	Core subject
Physical ergonomics		Anthropometry, body posture and movement, workstation design, biomechnics, repetitive movements and overuse, manual handling, workplace environment, tolos and eqiupment design
Cognitive ergonomics		Mental workload, information processing, decision-making, **h**uman-**c**omputer **i**nteraction (HCI), attention and vigilance, memory and learning, human error and reliability, situation awarness, automation and cognitive compatibility, stress and cognitive performance
Organizational ergonomics		Work design and job roles, communication systems, teamwork and collaboration, workplace policies and schedules, organization culture, change management, workflows and process optimization, leadership and decision-making, occupation health and safety policies, technology integrationa nd adoption, workpalce design and spatial layout, training and development

Cognitive ergonomics focus on optimizing human performance through thoughtful system design that reduces decision fatigue, streamlines workflows, and ensures that cognitive demands are aligned with workers” capacities [29, 35]. For instance, dashboards with excessive information or overly complex interfaces can lead to reduced efficiency and increased stress. E/HF principles aim to simplify data presentation and facilitate intuitive navigation to improve productivity and mental health.

TECHNOLOGY-DRIVEN TOOLS FOR E/HF IMPROVEMENT

Industry 4.0 has introduced a wide array of technologies aimed at improving E/HF [36, 37, 38]. Wearable devices, for instance, track physiological data such as heart rate, posture, and movement, providing real-time insights into workers” physical well-being. These tools help anticipate potential musculoskeletal issues or repetitive strain injuries, allowing for timely interventions and adjustments to work processes. Augmented reality (AR) and virtual reality (VR) are also transforming training and simulation within industrial settings [39, 40]. These immersive technologies help train workers in safe, controlled environments, reducing physical strain and the risks associated with high-stress tasks. Additionally, data analytics and machine learning algorithms enable predictive maintenance, ensuring that E/HF adjustments are proactively implemented, preventing workplace hazards.

In the age of Industry 4.0 the integration of advanced technologies has revolutionized the way E/HF is approached. With the rise of automation, artificial intelligence (AI), the Internet of Things (IoT), and real-time data analytics, organizations are leveraging technology-driven solutions to optimize worker well-being and enhance productivity. These tools not only improve physical comfort but also address cognitive and emotional demands in increasingly complex and automated work environments. Below some of the most prominent technology-driven tools and applications used to drive E/HF improvements are described.

Wearable technology

Wearable devices have emerged as a key tool for enhancing E/HF outcomes. These devices track various physiological metrics, including heart rate, body posture, movement, and activity levels, providing real-time insights into workers” physical well-being. For instance, smart wearables like fitness trackers, posture correction devices, and exoskeletons help prevent musculoskeletal disorders (MSDs) by offering constant feedback on E/HF performance [41]. Examples of applications of wearable devices: (1) posture monitoring – wearable sensors detect poor posture, alerting workers when adjustments are needed to reduce strain, (2) movement analysis – devices can track repetitive tasks, identifying risks associated with overuse of certain muscle groups, allowing for preventive action, (3) fatigue monitoring – monitoring physiological signals such as muscle fatigue can lead to customized break schedules and task adjustments. Benefits of wearable devices for E/HF are:

(1) real-time monitoring – wearable sensors track various physical metrics, such as posture, movement, and muscle strain, providing immediate feedback to workers,

(2) early detection – by collecting data on repetitive movements and poor posture, wearable devices can identify E/HF risks before they lead to injuries,

(3) personalized insights – Devices tailored to individual needs offer insights into personal E/HF habits, helping workers adjust behaviors to reduce physical strain.

By continuously monitoring E/HF indicators, wearable technology empowers workers to maintain healthy and efficient work patterns.

Augmented reality (AR) and virtual reality (VR) in E/HF training and simulation

AR and VR have transformed the way E/HF solutions are designed, offering immersive and interactive training experiences [42, 43]. These technologies enable workers to practice complex tasks in a risk-free virtual environment, reducing physical strain and minimizing errors when transitioning to real-world tasks. Examples of applications of AR and VR:

(1) safety training – workers can simulate hazardous situations, such as equipment malfunctions, without the physical risk, ensuring a safer work environment,

(2) task simulation – VR and AR provide realistic scenarios where workers can learn to optimize movements and handle repetitive tasks with precision, reducing the risk of injuries, (3) workstation optimization – physical tools, interfaces, and task design can be designed and tested virtually to identify issues before being implemented to reduce risk to workers once fully implemented.

Also, the interaction between these elements (tools, tasks, environments) before implementation can be presented virtuall before implementation in real-world environments. These tools help streamline training processes, ensuring that employees are familiar with ergonomic best practices before interacting with actual equipment. These technologies create a safe environment for workers to learn complex, high-risk tasks, practice E/HF adjustments, and gain confidence before applying these skills in actual work settings.

Artificial Intelligence (AI) and Predictive Analytics

AI-powered systems are increasingly being used to analyze data and predict E/HF risks. By leveraging data from wearable devices, IoT sensors, and workstations, AI can generate insights to proactively adjust workflows, minimizing strain and reducing the risk of injuries [44].

Examples of applications:

(1) predictive maintenance – AI systems analyze patterns in sensor data to anticipate when equipment may cause physical strain or malfunction, reducing downtime and optimizing E/HF conditions,

(2) task optimization – through machine learning, AI systems recommend adjustments to tasks based on past

performance, adjusting for factors like fatigue, motion, or stress levels,
(3) risk assessment – by correlating past data with potential hazards, AI can prioritize interventions to reduce E/HF risks in real-time.
This predictive capability allows organizations to take a more proactive approach to E/HF, minimizing physical discomfort and improving workplace safety.

Smart workstations and IoT-enabled environments
The Internet of Things (IoT) integrates sensors into workstations and environments, allowing for real-time adjustments to E/HF factors. Smart workplaces use data to adapt environments based on user needs, enhancing both physical comfort and efficiency. Examples of applications:
(1) adjustable workstations – smart desks, chairs, and monitor systems are equipped with sensors to adjust height, tilt, and other E/HF settings based on user feedback or automated adjustments,
(2) environmental optimization – IoT systems monitor lighting, temperature, and noise levels, optimizing workspaces to reduce physical strain and fatigue,
(3) collaborative work – IoT-enabled collaborative tools help teams work together while minimizing strain on their bodies, with real-time adjustments ensuring optimal E/HF support.
These technologies create highly personalized, adaptive workplaces that cater to the unique needs of individual workers.

Data-driven E/HF solutions
As organizations accumulate more data through IoT devices, AI systems, and wearable technology, they can create tailored E/HF solutions. By analyzing aggregated data, companies can gain deeper insights into specific E/HF challenges faced by different tasks, job roles, departments, or organizations [26]. Areas of E/HF using these kinds of solutions include:
(1) E/HF audits – through data analytics, companies can perform comprehensive E/HF assessments, identifying areas for improvement in workstations, workflows, and employee performance,
(2) customization – with big data, organizations can provide customized E/HF solutions that cater to diverse worker needs, whether it involves managing physical, cognitive, or emotional demands,
(3) continuous improvement – real-time feedback from wearable devices and IoT systems ensures that E/HF strategies evolve in response to the dynamic demands of the workplace.

Real-time feedback systems for E/HF optimization
Real-time feedback systems have become increasingly integral to the optimization of E/HF in the workplace. These systems collect data from sensors and wearable devices and provide immediate insights into physical and cognitive well-being [44, 45]. By continuously monitoring worker interactions with their environment, these systems help fine-tune E/HF components, ensuring the prevention of injuries and the promotion of a healthy, efficient workspace. Features and benefits of real-time feedback systems include:

1. Immediate insights: sensors embedded in workplaces or worn by workers provide continuous data on posture, movement patterns, and environmental conditions, delivering real-time feedback.
2. Customized adjustments: based on collected data, feedback systems suggest or automatically implement adjustments to workstations, task sequences, and workflows to suit individual E/HF needs.
3. Enhanced safety: continuous monitoring reduces the risk of repetitive strain injuries, providing proactive E/HF support to workers who may be handling physically demanding tasks.

These systems also integrate with other technologies such as IoT devices, ensuring that data is collected and analyzed seamlessly. By combining real-time insights with automation, organizations can create dynamic, responsive workplaces that adapt to the needs of workers in real-time.

INDUSTRY 5.0 AND E/HF
Industry 5.0 recognises that Industry 4.0 is too focused on technology and that re-introducing a more human-centred approach is required [46]. Instead, Industry 5.0 aims to address this by fostering industrial practice that has three qualities: human-centric, resilient, and sustainable [47]. In particular, because the term “human-centric” is fundamental to Industry 5.0 it could be argued that Industry 5.0 is therefore a a perfect fit for E/HF. Human-centricity isn”t just about ensuring human wellbeing in the presence of the types of advanced technologies already discussed, but also about improving human-technology collaboration so that humans can obtain maximum total benefits from the Exchange. However, in their review of the early studies on Industry 5.0 Alves et al. [47] found that the human-centric concepts had largely been driven by researchers (usually in the human sciences) rather than by industry or technology researchers. Another important aspect to highlight is that Industry 5.0 aims to support the development of industries that are sustainable. Thatcher [48] has shown how sustainability and E/HF are mutually compatible. A degraded environment is one that does not support health, wellbeing, or effectiveness, therefore E/HF initiatives that support sustainability, can also be viewed as supporting E/HF.

Sustainability and E/HF: A symbiotic relationship
In today’s fast-paced, technology-driven world, sustainability and E/HF are not mutually exclusive concepts. Instead, they complement each other, forming a symbiotic relationship that promotes healthier and safer workplaces while minimizing environmental impact. E/HF focuses on optimizing human performance and comfort, while sustainability aims to reduce the ecological footprint of organizational practices [48, 49]. Together, they aim to create work environments that are both people-centric and environmentally responsible [50]. E/HF plays a crucial role in fostering socially sustainable work practices by ensuring

that workplaces are designed to reduce strain, improve productivity, and support long-term employee well-being [48]. Sustainable ergonomics or green ergonomics not only focuses on physical health but also considers the environmental implications of workplace operations (the “green” side of E/HF). Creating energy-efficient and eco-friendly workplaces is a cornerstone of green ergonomics. This approach helps organizations maintain a balance between worker safety and ecological responsibility. This involves designing workspaces that optimize energy consumption while maintaining worker comfort and efficiency. E/HF solutions might integrate green technologies or ecological-thinking into the work and workplace design processes, promoting sustainability without compromising productivity. Some examples of strategies for an eco-friendly workplace design are:

1. Smart workstations/workplaces: adjustable, IoT-enabled workstations and workplaces adapt based on usage, reducing energy waste by turning off unnecessary lights, adjusting heating or cooling, and optimizing technology usage.
2. Sustainable materials: selecting eco-friendly materials for furniture, flooring, and equipment contributes to a reduced carbon footprint while maintaining comfort. Where multiple solutions are available, then choosing solutions that reduce resource use can contribute towards sustainability goals.
3. Natural lighting and ventilation: incorporating designs that maximize natural lighting and natural ventilation not only boosts worker well-being (through external views) but also lowers energy use for artificial lighting and climate control systems. Combined with the design of regionally-appropriate weather and seasonal clothing policies one can reduce energy consumption even further.
4. Active workplaces: the design of active workplaces (e.g., making stairs more visible, encouraging movement during work, taking active breaks, etc.) and physically-active commuting (e.g., walking or cycling facilities, including storage, showers, and changing facilities) can not only reduce general energy and resource consumption, but can facilitate a more physically healthy workforce.
5. Work-from-home: improving work-from-home technologies (including using VR and AR technologies) and practices to reduce the resources (and time) required for travel, thus improving productivity whilst also reducing environmental damage.
6. Choice of technology vs. manual work: appropriate understanding of task-demands can help make appropriate selections for when to choose a technological solution and when to choose a manually-operated solution. Just because humans can automate a task or process, or have developed an alternative technology, doesn”t necessarily mean one should use it in every circumstance. For example, an electronic sit-stand desk may be appropriate for people whose desks (when loaded with equipment) are heavy but is inappropriate if people are already moving around a lot or the desk only has a laptop (in which case a manually-operated sit-stand desk may be more appropriate).
7. Recycling: Applying E/HF one can design workplace activities so that either recycling is not needed (e.g., the appropriate design of a paperless office) or where recycling is made easy (collection points are appropriately located for the activities, and separation at source is made easy).

The sustainable designs presented above promote healthier workplaces while supporting long-term environmental goals utilizing eco-conscious technologies such as renewable energy sources, energy-efficient machinery, and waste reduction systems supports both environmental and E/HF goals (incorporating green technologies) [48]. However, it should be noted that fully embracing some Industry 4.0 technologies, especially AI and big data analytics, needs to be carefully managed due the high energy consumption required to use these technologies. While AI can certainly be used to find novel ways of reducing energy consumption [49], the responsible (and planned) roll-out of these technologies is therefore required to match workplace benefits with the expected increased in energy consumption and the production of e-waste [52].

A key challenge in promoting sustainable ergonomics is balancing worker well-being with environmental objectives. While sustainability seeks to minimize resource consumption and waste, E/HF focuses on optimizing human comfort and performance. Striking the right balance requires thoughtful integration of both concepts.

Sustainability and E/HF are intertwined in their pursuit of creating efficient, healthy, and responsible workplaces. Through thoughtful design, the integration of green technologies, and a focus on both human and environmental well-being, organizations can build work environments that promote sustainability without compromising comfort or productivity. As these principles continue to evolve, they pave the way for more sustainable and ergonomically sound workspaces that benefit both people and the planet.

THE FUTURE OF ERGONOMICS: TRENDS IN INDUSTRY 5.0 AND BEYOND

The evolution from Industry 4.0 to Industry 5.0 signifies a shift towards a more human-centric approach to automation and technology integration. While Industry 4.0 focused on optimizing efficiency through automation and data-driven decision-making, Industry 5.0 emphasizes a harmonious collaboration between humans and machines, placing worker well-being at the core of technological advancements [53].

Industry 5.0 is poised to redefine the relationship between technology and humans. Unlike Industry 4.0 which focused on the automation of tasks through artificial intelligence (AI), machine learning, and the Internet of Things (IoT), Industry 5.0 aims to build more adaptable, collaborative workplaces where humans and machines work side by side to optimize productivity and well-being. This shift acknowledges the limitations of fully autonomous systems and emphasizes the importance of integrating human input into decision-making processes [54, 55, 56].

The key characteristics of Industry 5.0 are as follows [57]:

1. Collaborative robots (cobots): cobots are designed to work alongside humans in dynamic, adaptive environments, offering physical support without taking over tasks completely.
2. Personalized automation: machines and AI systems will be tailored to individual worker needs, enabling a more customized approach to E/HF.
3. Emotional and cognitive wellbeing: Industry 5.0 focuses not only on physical ergonomics but also on mental health, reducing cognitive strain through better-designed work systems.

As moving into this new era, E/HF will continue to evolve, integrating advanced technologies and emphasizing personalization to create workplaces that enhance both productivity and employee well-being. The artificial intelligence (AI) and big data will create highly personalized E/HF solutions in Industry 5.0 [58]. Through continuous monitoring and analysis of worker data, AI systems are capable of tailoring work environments to individual needs in which physical, cognitive, and emotional factors are taken into account. AI-driven systems can adapt workspaces, adjusting seating, workstation layouts, and task prioritization to optimize comfort and efficiency (real-time adjustment). By analyzing past performance and health data, AI can predict future E/HF risks, providing proactive solutions to mitigate strain or discomfort (predictive analysis). Big data allows for a comprehensive understanding of workplace dynamics, addressing both physical tasks and emotional aspects of worker wellbeing, such as stress reduction and cognitive load management (E/HF holistic approach).

The personalized solutions from E/HF will create truly tailored environments for each individual worker.

CONCLUSIONS

While Industry 4.0 offers immense technological capabilities, ensuring the human-centric aspect of E/HF remains crucial. Designing work environments that seamlessly integrate automation with human skills requires ongoing research and adaptation. The goal is to create workplaces where technology enhances productivity without compromising health, safety, and overall well-being. As we advance toward Industry 5.0 – an era focused on human-centric automation-E/HF will continue to evolve, ensuring that technology works in harmony with human capabilities. The age of Industry 4.0 underscores the importance of an E/HF approach that embraces both technological innovation and human-centric design.

Technology-driven E/HF have become an essential component of modern industrial development. From wearable devices and AI analytics to AR/VR training and smart workstations, these tools empower organizations to create environments that prioritize both efficiency and worker well-being. As Industry 4.0 evolves, continuous innovation in these areas will pave the way for even more advanced, human-centered solutions that ensure workplaces remain safe, productive, and sustainable.

The future of E/HF is intertwined with emerging technologies that hold the potential to transform workplace environments. Wearable devices, augmented/virtual reality, and real-time feedback systems are revolutionizing the landscape of ergonomic solutions in the workplace. These technologies provide not only physical benefits, such as improved posture and reduced strain but also mental and cognitive support, enhancing overall well-being and productivity. The new tools will continue to shape the future of E/HF, ensuring safer, healthier, and more efficient working environments, and will continue to shape how workers interact with their surroundings, machines, and digital tools.

Industry 5.0 represents a significant evolution in how E/HF will be integrated into the workplace. Moving beyond simple automation, this new era emphasizes human-centric automation, tailored personalization through AI and big data, and the adoption of emerging technologies. As workplaces continue to embrace this holistic approach, E/HF will evolve to support a balanced, sustainable, and technologically advanced future where workers thrive both physically and mentally.

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