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THE EVOLUTION OF ERGONOMICS – FROM THE CONCEPTS OF WOJCIECH BOGUMIŁ JASTRZĘBOWSKI TO ERGONOMIC POLICIES OF ENTERPRISES IN THE ERA OF INDUSTRY 5.0

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Purpose: The article presents the trajectory of change in ergonomic research, beginning with the pioneering 1857 publication by Wojciech Bogumił Jastrzębowski and continuing to the present day (2025). The aim is to trace the development of ergonomic theory and practice in the context of advanced information technologies characteristic of Industry 4.0 and 5.0. The study seeks to highlight how integrating ergonomics into modern industry has transformed the discipline and what future ergonomic approaches must entail.
Design/methodology/approach: The objectives of the paper were achieved through a conceptual and historical analysis combined with elements of critical literature review and foresight. Rather than conducting empirical research, the authors trace the evolution of ergonomics from its origins in the 19th century to contemporary challenges associated with Industry 5.0. The approach is interdisciplinary, drawing from ergonomics, systems engineering, neurocognitive science, and social philosophy. The paper critically examines transformations in the human–technology relationship, forecasting the future role of ergonomics in increasingly automated and AI-driven environments.
Findings: The analysis reveals that the nature of ergonomics must fundamentally change in response to new conditions of human interaction with intelligent technical systems using artificial intelligence. The study shows that contemporary ergonomics increasingly extends beyond traditional applications, evolving toward human-centered organizational design. Moreover, the integration of ergonomic thinking into the design of objects and workplaces enables the discipline to synergize with systems engineering, enhancing its strategic role within enterprises.
Originality/value: This paper offers a unique historical-to-futuristic perspective on ergonomics, identifying its shift from a human-as-operator paradigm toward human-as-central-agent within technological systems. The value of the article lies in its relevance to researchers, system engineers, and enterprise decision-makers seeking to understand and implement ergonomic policies in the era of smart industry and human-centric automation.
Keywords: Human-centered design; Ergonomics; Industry 5.0; Ergonomic policy; Human-machine interaction.
Category of the paper: Viewpoint.

1. Introduction

The question regarding the role and future of ergonomics in contemporary enterprises is directly associated with the title of the lecture "Quo Vadis, Ergonomics?" delivered by Alphonse Chapanis, professor at The Johns Hopkins University in Baltimore, USA. This lecture was presented during the plenary session of the 7th Congress of the International Ergonomics Association (IEA), held in Warsaw from August 27 to 31, 1979 (Chapanis, 1979a, pp. 109-122; Chapanis, 1979b). In the final part of his lecture, the author offered an answer in a similarly styled phrase: Urbi et orbi (to the city and the world). This indicated that ergonomics addresses both micro-level issues, such as individual workstations and other forms of human-technology interaction, and macro-level concerns, namely, the broader impact of technology on society, including its cultural, economic, social, and political dimensions. This second area of research has since become known as macroergonomics (Hendrick, 1987, 2000; Pacholski, Jasiak, 2011).

While microergonomic issues appeared relatively rational and well-defined, the ergonomics concept for complex systems seemed distant, even abstract. The perceived clarity of microergonomic challenges stemmed from the belief that workstations and practically all related work tools could be adapted to human needs through “common sense”. A lack of ergonomic design in such objects was often regarded merely as an oversight, rather than as a scientific or even engineering issue. The challenge of adapting technology to human needs, often referred to for years as the "humanization of work", has never been as critical as it is today. The question posed by A. Chapanis 45 years ago remains highly relevant, and today's answers often provoke concern, even fear, for the future of humanity.

Wojciech Bogumił Jastrzębowski was the first scholar in the world to propose developing knowledge about humans assisted in their work by technical means, and he coined the term ergonomics (Jastrzębowski, 1857). This idea remained forgotten for almost a century, likely due to its pioneering nature and the fact that societies of the time were not yet advanced enough to embrace it, relying on simple tools and ignoring the physical condition of workers. But didn’t our ancestors, Homo habilis (“handy man”), who began crafting and using hand tools made from stone, bone, and wood at least 2.5 million years ago, have to adjust their shapes to match the structure of their hands, movement capabilities, and strength? One might argue that “intuitive ergonomics” has been developing for 2.5 million years, while the past 80 years of consciously developed ergonomics represent only 0.0032% of that time, a statistically negligible period (Tytyk, 2019, p. 41).

As technical tools have become increasingly advanced and complex, methods of ergonomic diagnosis and design have also evolved. This is due to the need to meet new demands from people who create and use sophisticated technical products. Since the field’s inception, initially as a theoretical proposal (by W.B. Jastrzębowski in 1857), followed by practical applications (by engineers in the U.S. Army during World War II), through post-war industrial reconstruction and development, to the current era of deep automation and robotics known as the Fourth Industrial Revolution (Industry 4.0) - ergonomic efforts have shown a clear trajectory. An analysis of these developments enables us to outline the path of ergonomic evolution in the context of the emerging Fifth Industrial Revolution (Industry 5.0), which we are now entering. This will undoubtedly be a different type of ergonomics than what we knew in the 20th century. The aim of this analysis is to forecast a vision for the development of ergonomic research methodology and methods during the era of Industry 5.0.

2. XXth Century Ergonomics

At the end of World War II, a pressing need emerged to adapt aircraft control systems and other military technologies to the capabilities of their human operators. Quite simply, people could no longer control the products of their own minds and hands. This marked the beginning of the "golden era of ergonomics," as it became clear that machines, hand tools, other technical devices, and the work environment, when adjusted to human abilities and limitations, enabled improved economic outcomes from human activity. At the foundation of ergonomic success, then (as now), was economics.

Ergonomics during this period was shaped by a symbiosis of physiology, psychology, medical sciences, anthropometry, acoustics, and optics. From the second half of the 20th century, ergonomics focused on individual workstations in industry, automated assembly lines, computer-based work environments, as well as the work of doctors, drivers, teachers, athletes, household activities, leisure-time tasks, persons with disabilities, and senior citizens. This era saw a surge of scholarly publications, research reports, and conference presentations both nationally and internationally. Ergonomic concerns were taken up by professionals across many sectors, including industry, agriculture, furniture manufacturing, architecture, urban planning, occupational safety, design, and management.

In Poland, as in other countries, research methodology in ergonomics developed in two main domains: corrective ergonomics, focused on ergonomic diagnostics (Pacholski, 1977), and conceptual ergonomics, aimed at ergonomic design (Tytyk, 2001). Practical and actionable methods for issuing standardized ergonomic recommendations for industrial products were also proposed, enabling the marketing use of ergonomic quality features (Górska, Tytyk, 2017, pp. 93-110). Furthermore, ergonomics was applied in situations involving shortages in human resources, such as among people with disabilities (Butlewski, 2018).

At the beginning of the 21st century, the topics presented at conferences, especially in Poland, began to suggest a depletion of new research ideas, sometimes even provoking confusion. While subjects like "kitchen or bathroom ergonomics" had legitimate merit from a human–technology interaction standpoint, other topics, such as ergonomic considerations in necropolis architecture (including vertical burial systems!), elicited embarrassment.

Despite Poland being the homeland of the field's forerunner, W.B. Jastrzębowski, ergonomics still does not hold the status of an academic discipline in the country. A classic case of "the shoemaker's children go barefoot"? Since it has not been possible to attain academic promotion solely through work in ergonomics, the subject had to be "smuggled" into other academic disciplines, a task that was neither easy nor always convincing. As a result, young researchers, at the beginning of their careers, were discouraged from pursuing such a risky and interdisciplinary topic. Consequently, ergonomics has become an increasingly hermetic field, practiced by a small group of aging researchers whose academic achievements lie mainly in other disciplines. This led to hybrid professional identities, such as mechanical engineer–ergonomist, physiologist–ergonomist, physician–ergonomist, psychologist–ergonomist, and architect–ergonomist.

Despite these unfavorable academic conditions, ergonomic knowledge continued to prove its value in practical applications. Market dynamics demanded the incorporation of ergonomic principles in the design and production of goods, as poor ergonomic quality (by contemporary standards) discouraged buyers, who opted for competing products that offered a better balance between quality (including ergonomic quality) and price. This is clearly visible in the markets for passenger cars, certain furniture (especially for computer workstations), and hand tools. Ergonomic quality became a marketing and advertising asset, an argument for increasing the product price. This is, however, entirely rational: higher-quality products, whether in terms of design, execution, aesthetics, ergonomics, safety, or ease of maintenance, justify higher prices. It is an investment that eventually pays off, yielding above-average returns. Nevertheless, this practical and theoretical aspect of ergonomics has so far received little attention from economists and market researchers, a somewhat surprising oversight.

A further distinction must be made between ergonomics and occupational safety and health (OSH), or more formally, occupational safety engineering. The aim of both scientific and practical ergonomic work is the adaptation of technical objects to human capabilities and preferences, that is, the humanization of technology. This adaptation leads to more effective human performance, especially in professional work, while reducing excessive physical and mental strain. However, demonstrating the economic benefits of ergonomic interventions is not straightforward, which complicates efforts to persuade business leaders to invest in ergonomic technical and organizational solutions. Furthermore, ergonomic requirements are not legally binding in Poland, ergonomic standards can simply be ignored.

In contrast, OSH aims to ensure the safety of the human body and psyche by reducing the frequency and severity of work-related accidents (as sudden events) and limiting the occurrence of occupational diseases (as long-term effects of excessive strain and poor environmental conditions). The costs of accidents and occupational illnesses are relatively easy to quantify, and occupational safety and hygiene are enforced through mandatory legal regulations and standards cited in ministerial and governmental ordinances. These obligations are also embedded in the Polish Constitution (Articles 24, 66, and 68) and the Labor Code, Chapter X.

Thus, we can say that the primary goal of ergonomics is the economics of human activity, whereas the main mission of OSH (or occupational safety engineering) is humanitarian. However, these two fields intertwine in such a way that ergonomics is sometimes seen as a continuation or extension of OSH, while in other interpretations, OSH encompasses ergonomic activities. In practice, however, safety solutions can be non-ergonomic (e.g., certain types of personal protective equipment), and ergonomically correct solutions may fail to ensure adequate safety (e.g., some powered hand tools).

3. Ergonomics at the turn of the 20th and 21st centuries

The dominant paradigm in ergonomics assumes that its subject of study is a system composed of a human (or humans) and technical objects (functional artifacts) used in conscious action. This implies a dual structure: two distinct and separate subsystems, the human and the technical. Today, this categorical division is no longer as evident. Are technical elements truly separate from the human being? Jan Jabłoński (Jabłoński, 2020) introduces the "mediated human" concept, a person whose actions are facilitated through technical intermediaries such as tools and machines.

No one is surprised by canes, crutches, walkers, wheelchairs, hearing aids, or corrective lenses. These external technical objects support human functioning, often making life easier or even possible. For nearly 3000 years, technical objects have been "embedded" in the human body to replace or imitate natural organs. As early as 700 BCE, the Etruscans in central Italy crafted partial dental prosthetics known as bridges (James, Thorpe, 1997, p. 44). Around the same period, both Europe and India began producing limb prostheses, often necessitated by war injuries (James, Thorpe, 1997, p. 46).

Today, such support for human life functions is insufficient without advanced medical technologies. Implants, dental, hip, and knee, as well as highly functional limb prostheses and pacemakers, are widely used. Modern prosthetics can be controlled via muscle bioelectric signals, providing functionality comparable to biological limbs. Does this fall within the scope of ergonomics? Undoubtedly, because these user artifacts must be fitted not only geometrically but also biochemically (e.g., avoiding toxicity or allergic reactions).

But how should we interpret technical solutions that become integral parts of the human body? This necessitates a redefinition of the ergonomic system to include a more integrated interpretation of the human–technical object relationship.

Modern health concepts extend beyond medical or psychological care. Alongside the desire to maintain overall health, defined by the WHO as a state of physical, mental, and social well-being, there is now an active pursuit to extend life, enhance cognitive capabilities (augmented cognition), and guide the course of human evolution toward improvement. While we are still in the early stages of engineering in this domain, we can now continuously monitor and respond to bodily parameters, repair joint and dental damage with implants, track internet activity and consumer behavior, and even perform facial recognition. These capabilities enable constant surveillance of individuals, ostensibly for their safety and benefit, but also for more dubious purposes, as evidenced in countries like China. The body is not the only site of technological intervention. Efforts are now underway to augment cognitive abilities through electronic brain implants, linking the brain to external computers and merging natural intelligence with artificial systems (e.g., Neuralink). This trajectory leads us toward human–machine hybridization, or cyborgization, birthing a new class of techno-human beings.

This direction of development has given rise to a philosophical movement known as transhumanism. Max More (More, 1990) defines it as "a class of philosophies that seek to guide us toward a post-human condition. Transhumanism shares many elements with humanism, such as respect for reason, science, and progress, but diverges in its openness (even eagerness) for radical changes to human nature through science and technology."

This resembles a dangerous "play at being God", a being who, in any religion, holds exclusive rights to create life yet is accountable to no one. From a Buddhist perspective, such enhancement might aim toward nirvana, while in other religions, it may equate to a heavenly state of eternal bliss. The danger, however, lies not in breaking taboos but in our still-fragmentary understanding of life itself, and our inability to foresee the consequences of such "play". Transhumanism (also labeled Humanism+) is based on the assumption that ancestral cultures have failed to resolve humanity's problems and instead have created new ones. Therefore, they should be abandoned in favor of engineering a new human being and a new society. Such socially-engineered projects, supported by relatively primitive technologies in recent history (e.g., eugenics), have had tragic consequences. We should not use technologies we don't fully understand, because the outcomes may be catastrophic.

Isaac Asimov foresaw these dilemmas in *The Complete Robot*, though he did not use the term transhumanism. In it, he formulated his famous "Three Laws of Robotics" (Asimov, 1993):

1. A robot may not injure a human being or, through inaction, allow a human being to come to harm.
2. A robot must obey orders given by humans, except where such orders would conflict with the First Law.
3. A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.

Despite their theoretical logic, these laws produced unexpected and often negative consequences in practice. Especially notable is the chapter "The Bicentennial Man" (pp. 407-466), which explores the transformation of a man into a robot, and vice versa.

Contemporary ergonomics is beginning to explore the goals and methodologies required to examine human cyborgization scientifically. In Poland, institutions such as the Jagiellonian University (Department of Neurocognitive Science and Neuroergonomics), the University of Information Technology and Management in Rzeszów (Laboratory of Neurocognitive Ergonomics), and Kazimierz Wielki University in Bydgoszcz (Tomaszewska, 2021) have begun addressing these topics. Neurocognitive ergonomics is considered a subdiscipline of ergonomics. It focuses on cognitive processes during human interaction with the environment, examined using neurocognitive methods such as EEG, EMG, eye-tracking, and neuroimaging. These tools are employed in studies of user preferences in human–computer interfaces, neuromarketing, attention management, decision-making processes, usability evaluation, mental overload, stress (or monotony), and human error during interactions with technical systems. These findings are critical in shaping the working conditions of Industry 5.0. At the 3rd National Ergonomics Congress (Gliwice, June 28, 2024), such topics were discussed.

Ergonomic challenges in the field of advanced automation and robotics, especially when integrated with artificial intelligence, concern the design of systems and components that are readily accessible, even intuitive, during mental operations performed by humans interacting with technical devices. At the same time, there is a growing need to adapt humans to this sophisticated, increasingly AI-driven technology. This requires targeted education and psychological preparation for working within such technical environments. One emerging concept in this context is cobotics, the close cooperation between humans and robots. It is telling that children enjoy playing with toys that are, in fact, increasingly functional robots resembling animals or even other children. In many schools and universities, starting in Switzerland and, since 2011, in various other countries, the autonomous humanoid robot Nao has been used for educational and research purposes (Nao Robot Power V6). The sight of a five-year-old child absorbed in a smartphone, barely responsive to the outside world, is becoming a common example of a cyber-child. This should serve as a warning about the risk of mental manipulation and indoctrination of young, impressionable minds. Is this already happening? We must ask ourselves. This raises a fundamental question within the context of this discussion: What role can ergonomics play in addressing these challenges?

Changes in professional activity are also being driven by the application of advanced technology. In 2019, it was predicted that 47% of existing professions could disappear within the following 10 years, replaced by robots and artificial intelligence. In turn, there will be a growing demand for skills in STEM fields (Science, Technology, Engineering, and Mathematics) (Hatalska, Trapp, 2019). This shift will trigger not only new ergonomic challenges but also issues in social policy, economics, and education. Structural unemployment may emerge, as well as the rise of the so-called "surplus citizens", individuals deemed economically unnecessary, as Edwin Bendyk (Bendyk, 2018) calls them. Other side effects may include the growth of the precariat, and increased labor-related migration and emigration.

Ergonomists cannot solve these problems alone, but they can propose technical solutions to at least some of them. The ideal (following Abraham Maslow's hierarchy of needs) is a model of work organization known as "teal organizations", a concept coined by Frédéric Laloux (2016). This model envisions work undertaken freely, without coercion, aligned with a person's interests, qualifications, capabilities, and intentions. It is inherently linked with self-actualization, the highest need in Maslow's hierarchy. Will this be the future of work in a world dominated by Artificial Intelligence (AI) and the Internet of Things (IoT)? We can already observe that the role of humans in relation to machines is evolving in a specific direction: from system operator to supervisor of autonomous technical systems. There are valid concerns that this shift may not universally lead to the "teal" model of work, but perhaps a select group of people, high-level AI and IoT experts, will have the opportunity to experience it. These individuals will hold esoteric, almost shamanic knowledge, inaccessible to most others. The majority will remain users of technical devices whose inner workings they neither know nor need to understand. These complex and mysterious technologies will shape the living and working conditions of the majority, creating a dependency on the knowledge and ethics of a narrow group of technology creators. In an interview with Jacek Żakowski for Polityka, Bulgarian political scientist Ivan Krastev stated with bitter clarity: "We are no longer trying to build great societies. We are simply trying to save them from the apocalypse" (Polityka, 29/2020, p. 19). Similarly, in an interview with Tonje Hessen Schei, director of the documentary iHUMAN about artificial intelligence, the CEO of Microsoft warned: "We must decide not what technology can do, but what it should do" (Polityka, 36/2020, p. 77). Such statements, echoed by other influential thinkers, indicate a growing awareness of the long-term consequences of today's technological decisions, far beyond immediate economic and political gain. AI is now the foundation for developing autonomous transportation systems, road, rail, maritime, and air, that do not require human operation. For years, passenger aircraft such as the Boeing 737 and Airbus A320 have included Flight Management Systems (FMS), which are capable of partially autonomous flight control. In 2019, a fully automated take-off of an Airbus A350 was successfully tested at the Toulouse airport in France. Clearly, knowledge in building and managing autonomous transport has been accumulating for some time.

In Poland, interest in such innovations is growing, for example, the BB-1 Blees autonomous bus is currently being tested in Gliwice. In passenger transport, people are treated as passive cargo to be moved from point A to B under full digital control. Such solutions are already commonplace in major airports (e.g., terminal shuttles) and in subway systems in large cities.

There are also ongoing experiments with autonomous freight transport, air taxis, and even combat drones. Extensive experience has already been gathered in designing unmanned spacecraft, drones, and naval vessels, as illustrated by recent warfare in Ukraine.

These developments demonstrate a tendency to eliminate the human element, considered the most fallible and costly part of the system, in favor of automated solutions.

However, in atypical, unpredictable, and emergency situations, the human being remains irreplaceable. Unlike machines, humans can act on intuition and instinct, not merely through pre-programmed routines. Yet this raises another issue: legal and moral responsibility. Who, or what, will be held accountable for an accident involving an autonomous vehicle or aircraft? What consequences should be imposed? Clearly, technological progress in autonomous transport introduces new legal, economic, and social challenges. From the perspective of human–technology interaction, one can identify fertile ground for the further development of neurocognitive ergonomics.

4. The need for new ergonomics

In the contemporary context, it is essential to ask what form modern and future ergonomics will take. Is the traditional version of ergonomics, focused on human–technology interaction as it has been understood since the mid-20th century, facing its natural decline? This seems to be a rational and increasingly accurate conclusion, especially in technologically and economically advanced societies. The cause of this transformation lies in civilizational progress itself, which has led to the emergence of a customer-driven market. In such a market, the oversupply of manufactured goods coexists with a limited pool of buyers. Consequently, producers must compete for consumer attention and loyalty, offering products that are attractive in both price and quality.

To stand out, companies increasingly turn to sophisticated marketing strategies, including neurocognitive techniques, known as neuromarketing. Yet these methods alone are insufficient to generate demand; objective product features, especially the price-to-quality ratio, remain decisive. Among product quality factors that shape consumer preferences, ergonomics, defined as the degree to which a product satisfies human-centered design criteria, plays a crucial role. Though the term itself may seem technical, more accessible alternatives, such as user-friendly, are commonly used. Manufacturers who neglect ergonomic quality risk market exclusion by competitors who, even without directly referencing ergonomic design, produce products that better fit user needs. Thus, ergonomic excellence not only justifies higher prices but also underpins business success.

Despite its practical significance, ergonomics as a discipline must now seek new fields of inquiry. These may lie in the development of artificial intelligence (AI), the Internet of Things (IoT), virtual and augmented reality (VR/AR), and advanced machine learning tools such as ChatGPT. Indeed, global trends in industry and human activity provide promising directions for ergonomics, particularly through the concept of Industry 5.0. Unlike Industry 4.0, which emphasized the integration of AI, IoT, and data analytics into autonomous systems, Industry 5.0 focuses on collaboration between humans and machines. This shift necessitates not only technological innovation but also psychological and emotional adaptation on the part of human workers.

The overarching goal is to develop intelligent, autonomous production systems that improve efficiency and flexibility while cooperating with humans, who, although error-prone, remain essential participants in complex processes. This new paradigm opens substantial research potential for ergonomics, particularly in understanding how humans interact with automated systems. Areas of growing relevance include collaborative robotics (cobots), immersive technologies (VR and AR), and next-generation connectivity like 6 G. VR and AR, for example, allow for realistic simulations of workplace environments, thereby enhancing ergonomic prototyping and testing.

In parallel, the field of neuroergonomics, which explores the interaction between the human brain and technology, is expanding. Research focuses on cognitive processes such as sustained attention, decision-making, stress management, and error prevention in technologically intensive environments. These concerns are particularly relevant in the face of mass product personalization, which demands flexible workstation and tool design. Traditional ergonomic approaches based on predefined measurement frameworks may soon be replaced by dynamic adaptation to specific user groups. This shift poses significant challenges in terms of flexible production system design, but also opens possibilities for interactive, personalized products tailored to innovative user needs.

Such innovation is increasingly extending into domains previously considered less dynamic, such as gerontechnology. This field transcends basic telemedicine and seeks to develop technology with and for older adults, framing them as “innosumers”, innovative consumers (Peine, Rollwagen, Neven, 2014). Rather than merely responding to stated user needs, future ergonomic design will anticipate potential needs and adapt in real time. This anticipatory, personalized model of ergonomics aligns with broader societal and technological trends, including sustainability and workforce resilience.

Indeed, principles of sustainable development and production system resilience demand that organizations address the mental well-being of employees, an area that increasingly intersects with ergonomic research. While well-being has a psychological component, achieving it will also require engineering efforts aimed at shaping how individuals function in their work environments. As such, ergonomics will play a vital role in social responsibility (SR), one of the key pillars of ESG (Environmental, Social, and Governance) reporting. Although ESG standards remain under discussion in early 2025, they will eventually integrate environmental, social, governance, and ethical dimensions. Ergonomics fits seamlessly within this framework by promoting better working conditions and employee well-being, supporting human health and organizational performance (Butlewski, Czernecka, 2024).

Moving forward, integrating emerging technologies and adopting interdisciplinary approaches will be essential to the evolution of ergonomics, particularly within the context of Industry 5.0 and sustainable development. The classical ergonomic concern with human–technology systems must now address increasingly autonomous technologies, such as robotics and automation, which minimize direct human intervention. The role of humans is shifting toward coordination, supervision, calibration, and maintenance. As technologies advance, so too does the importance of maintenance professionals, who must possess specialized knowledge and specific psychological aptitudes. Designing appropriate work environments for these professionals requires refined ergonomics, especially neuroergonomic expertise.

Meanwhile, service-sector occupations, such as retail, banking, tourism, education, and research, present entirely different ergonomic challenges. These roles typically involve intellectual labor and interpersonal interaction rather than constant engagement with technology. Here, ergonomic concerns are shaped less by engineering and more by psychology and sociology. Nonetheless, they remain firmly within the purview of modern ergonomics.

5. The need for ergonomics policy in enterprises

Given the aforementioned circumstances, particularly two elements: the increasing humanization of technical means and the growing number of such means in the human environment, a key question arises. Should workplaces be subject to special protection or intervention from employers, in light of the environment's impact on employees on one hand, and the continuous improvement of these systems' ergonomic efficiency on the other? Can a perfect work system emerge spontaneously, or should it be developed similarly to a digital twin of the entire enterprise? As explained in the first part of the article, ergonomic efficiency accounts for the long-term ability of an employee to contribute added value, so is it not justified to model this value? Are current efforts in this field, primarily involving production process modeling and occupational risk management with a touch of ergonomics focused on musculoskeletal disorders, sufficient? The necessity of addressing these questions becomes increasingly evident, as illustrated by the growing attention to employee well-being. The ergonomic quality of a workstation results from long-term activity, where the worker’s well-being may be threatened by prolonged exposure to negative factors in both the technical and social work environment (e.g., fatigue, illness, burnout, reduced performance).

It can therefore be concluded that modern workplaces are undergoing dynamic changes driven by technological progress, automation, and the implementation of artificial intelligence. Accordingly, ergonomics faces multiple challenges that are crucial for businesses to address. One of the major areas is the integration of humans with systems powered significantly by decision-making algorithms based on machine learning and automation. This raises issues such as the need to adapt work interfaces to employees' cognitive and physical capabilities while accounting for human error; the necessity to supervise decision-support systems in a way that avoids dehumanization (for instance, credit decisions should not rely on black-box processes, as the individual decision variables must be traceable); and the risk of "mental deactivation" among employees who merely oversee automated processes and may lack the cognitive readiness to act when intervention is required, an issue known as the "back in the loop" effect (Inagaki, 2008).

Another area of concern is cognitive ergonomics and the prevention of mental overload, which manifests in practice through potential challenges such as burnout caused by the pace and nature of work; the need to design systems that reduce informational stress and support effective attention management in today's attention economy, where being constantly online and responding swiftly to messages is equated with productivity, even though it may, in fact, be counterproductive; and the development of ergonomic work environments that promote focus and creativity, while addressing deficits in modern workplaces, such as a lack of interpersonal interactions.

A further domain involves the implementation of work hygiene and, more broadly, an ergonomic approach to hybrid and remote work. This includes designing ergonomic home workstations to minimize health risks (e.g., back or wrist pain, occupational hazards); optimizing digital tools to support effective communication and collaboration while meeting the criteria outlined above; and separating work and private life, not only to support employee well-being (including family life), but also to ensure work efficiency and avoid environments that encourage procrastination.

Additionally, efforts are needed to counteract health threats stemming from digital environments. This includes preventing physical and mental health issues associated with sedentary lifestyles and limited physical activity, a phenomenon increasingly resembling an epidemic, affecting both the musculoskeletal and peripheral nervous systems as well as mental health (e.g., work-related depression).

Integrating ergonomics and neuroergonomics into enterprise processes is another important area, particularly through the use of biosensors. This includes deploying biometric sensors and monitoring systems to track body posture during work, fatigue levels, or stress; intelligent office components that adapt to users or their current needs (prompting specific behaviors); and personalized system settings tailored to individual users and their physiological or psychological states.

Ergonomics can be a valuable tool in implementing company strategies, supporting both ethical and social dimensions of work in the digital era. It can help strike a balance between digital quality control and the protection of employee privacy, aiming for efficient management without compromising worker autonomy. Moreover, well-designed work systems can remove barriers related to age, digital skills, or disabilities, fostering more inclusive workplaces focused on performance. In this context, ergonomics enables the de-ideologization of inclusion processes, i.e., inclusion is not pursued solely for its own sake. Companies can use ergonomic design to support the learning of new technologies among digitally inexperienced individuals and to implement solutions that encourage prolonged professional activity. Despite the outlined development challenges, ergonomics still holds significant potential, not only to enhance comfort and efficiency at work but also to promote sustainable and responsible work environments.

The development of ergonomics in contemporary workplaces requires an interdisciplinary approach that combines technology, psychology, occupational medicine, and human resource management. The primary objective is to ensure working conditions that support employees' health, effectiveness, and well-being while seamlessly integrating them into rapidly evolving work systems.

6. Conclusions

The above considerations, which concern the historical evolution of ergonomics methodology, authorize the formulation of several cardinal questions that demand rational and evidence-based answers. First, which areas of the interdisciplinary field known as ergonomics should be further developed, and is it necessary to redefine its goals and the scope of its research and practical activities? Second, what is the role of ergonomics within an enterprise, and how can its principles contribute to improving work efficiency, employee well-being, and organizational innovativeness, an issue closely tied to the first question?

Third, will ergonomics, as a distinct scientific discipline developed for over 80 years, become obsolete in the future, having exhausted its developmental potential and become absorbed by technical, organizational, and economic knowledge? This question leads to a further one: is there any value in distinguishing ergonomics as a separate discipline, or should it instead be integrated into existing academic fields and appropriately subdivided among them?

Fourth, how should we conceptualize the science (or knowledge) of the system comprising humans and technical objects, especially when the human is increasingly functioning as such a system, for example, when decision-making is significantly influenced by suggestions from a personal assistant embedded in a mobile device? In connection with this, should we not pursue the development of knowledge at the intersection of systems engineering and ergonomics?

Another important question arises: how can we define ergonomic problems when technical objects become essential parts of the human body, and the human-cyborg collaborates with robots equipped with artificial intelligence (AI), exchanging information via the Internet of Things (IoT)? This leads to yet another, perhaps the most radical, inquiry: will the physical capabilities and intelligence of humans, rendered irrelevant and unnecessary, ultimately be replaced by infallible and dehumanized technical environments?

While these questions are philosophical in nature, they also carry substantial practical implications. For instance, the issue of human capacity in the context of technical support systems is becoming increasingly significant, as the combined capacity to perform tasks will determine work outcome assessments. Consequently, the competency profile required in Industry 5.0 enterprises is undergoing a profound transformation.

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