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Integrating human-centric simulations in educational production lines: advancing ergonomics for industry 5.0 applications

Aitor Ruiz de la Torre [a1*], **Jon Borregan** [b], **Naiara Pikatza** [b2], **Rosa Maria Rio** [a2]

[a] Industrial Organization and Management Engineering Dept. Faculty of Engineering Vitoria-Gasteiz. University of the Basque Country UPV/EHU. Nieves Cano 12, 01006 Vitoria-Gasteiz, Spain.

[b] Industrial Organization and Management Engineering Dept. Faculty of Engineering Bilbao. University of the Basque Country UPV/EHU. Paseo Rafael Moreno 'Pitxitxi' 2, 48013 Bilbao, Spain.

[a1] aitor.ruizdelatorre@ehu.eus, [b1] jon.borregan@ehu.eus, [b2] naiara.picaza@ehu.eus, [a2] rosamaria.rio@ehu.eus

Abstract:

This research in the Industry 5.0 field focuses on a human-centered simulation of the FAS200 SMC educational production line, utilizing Tecnomatix Process Simulate Human software for developing a virtual human environment. A key aspect of this study is the integration of inertial sensors, enhancing the accuracy and depth of ergonomic analysis. These sensors play a pivotal role in capturing precise human movement data, crucial for ergonomic assessments. Adopting a defined working methodology, the study extensively employs the RULA method to evaluate operator postures in the production line. This approach has led to significant ergonomic improvements, evidenced by a 40 percent reduction in the RULA index at each workstation. The integration of inertial sensors has been instrumental in achieving these results, providing detailed insights into human movements and interactions with the production environment. The research transcends traditional ergonomic assessments by incorporating a new human-centered approach, emphasizing the well-being of individuals working alongside machines. This approach, bolstered by the use of inertial sensors, marks a significant advancement in ergonomic studies, aligning with the principles of Industry 5.0. The findings hold substantial potential for application in industrial settings, signaling a shift towards more human-friendly and efficient industrial practices.

Key words:

Industry 5.0, human-centered production, simulation, ergonomics, inertial sensors, digital twin.

1. Introduction

Industry 4.0 marked a significant shift in industrial development, characterized by the adoption of advanced technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and automation. This evolution aimed at enhancing operational efficiency and connectivity within the manufacturing sector (Leng et al., 2022). As Industry 4.0 progressed, it paved the way for the emergence of Industry 5.0, which focuses on integrating these technological advancements with a more human-centered approach to production (Zizic et al., 2022).

Expanding on this trajectory, Industry 5.0 transcends the technological emphasis of its predecessor, blending the cutting-edge advancements of AI, IoT, and automation with a renewed focus on human ingenuity and sustainability. This evolution not only retains the operational efficiency gains of Industry 4.0 but also embeds a more holistic approach in manufacturing processes. The goal of Industry 5.0 is to strike a balance between automated efficiency and the creative, problem-solving abilities of humans, thereby fostering a more adaptive and resilient industrial environment.

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In this context, the advent of Industry 5.0, building on the technological foundation of Industry 4.0, represents a paradigm shift towards three main focus groups: human-centered approach, sustainability, and resilience. This transition marks a significant advancement in industrial development, aiming to harmonize the capabilities of cutting-edge technology with the unique attributes of human ingenuity, thus embodying a more balanced, efficient, and sustainable industrial future.

At the core of Industry 5.0 is the integration of human intelligence with advanced technological systems. This human-centered approach emphasizes the value of human creativity, problem-solving, and decision-making skills in conjunction with automated processes, ensuring that technology enhances rather than replaces human work (Ivanov, 2022).

In terms of sustainability, Industry 5.0 prioritizes sustainable manufacturing practices, going beyond economic considerations to include environmental stewardship. It aims to create production processes that are not only efficient but also environmentally responsible, reducing waste and minimizing ecological impact (Grabowska et al., 2022).

The third pillar of Industry 5.0 is building resilience in manufacturing systems. This involves developing adaptive and flexible processes capable of responding to various challenges, such as market fluctuations and environmental crises. Resilience in Industry 5.0 ensures that manufacturing systems can withstand and recover from disruptions effectively (Jafari et al., 2022).

The first significant benefit of Industry 5.0 is its human-centered approach. By integrating human intelligence with advanced technological systems, Industry 5.0 enhances the role of human creativity and decision-making in the manufacturing process. This approach results in improved problem-solving, innovation, and overall job satisfaction, leading to higher productivity and quality of work. A study by Marjanovic, (2013) emphasizes the importance of human-centered knowledge sharing in data-driven decision-making, highlighting how this approach can lead to ongoing improvement of complex processes in industrial settings (Marjanovic, 2013).

The second benefit pertains to sustainability. Industry 5.0 prioritizes sustainable manufacturing practices, which extend beyond the boundaries of economic benefits to include environmental stewardship. This shift leads to more efficient production processes that are environmentally responsible, helping to reduce waste and minimize ecological impact. Research by Fatima et al. (2022) discusses the role of IoT in enabling digital transformations in Industry 4.0 and how the objective shifts in Industry 5.0 to achieve maximum benefits through human-machine interaction, furthering the cause of sustainability (Fatima et al., 2022).

Finally, resilience forms the third cornerstone of Industry 5.0. It involves developing adaptive and flexible processes to respond effectively to various challenges such as market fluctuations and environmental crises. This resilience ensures that manufacturing systems can withstand and recover from disruptions effectively. A study by Leng et al. (2023) provides a comprehensive overview of resilience in Industrial Internet of Things systems, highlighting the importance of resilient communication and methodologies for enhancing the resilience of industrial systems (Leng et al., 2023).

In addition to the overarching benefits of Industry 5.0, there are several key advantages that specifically address workplace dynamics and broader societal impacts. Industry 5.0's focus on human-centric approaches has revolutionized workplace dynamics, leading to enhanced safety, improved employee well-being, and sustainable production practices. By utilizing advanced technologies like AI and IoT, not only for efficiency but also to monitor and improve workplace safety conditions, Industry 5.0 has substantially reduced workplace accidents and health hazards, as discussed by Boschetti et al. (2023) in their exploration of human-centered design in collaborative robot cells. Additionally, the integration of human intelligence with technology in Industry 5.0 places a high value on the mental and physical well-being of employees, enhancing employee satisfaction and well-being, which is pivotal for productivity and innovation. Rajendran et al. (2022) underscore this point by describing a multi-agent safety system for human-robot collaboration, employing wearable technologies like the Apple Watch to monitor and enhance employee well-being. Moreover, Industry 5.0 extends its focus to sustainable production practices that go beyond environmental concerns to include sustainable business models, accounting for long-term societal and planetary impacts. This is evident in the work of Colla et al. (2021), who highlight the integration of robotics solutions in the steel shop to improve health, safety, and sustainability. Together, these advancements underpin Industry 5.0's commitment to creating a more balanced, safe, and sustainable industrial environment.

Emphasizing the clear advancements made by Industry 5.0, it's evident that this latest phase in industrial development significantly builds upon the technological achievements of Industry 4.0, while placing a greater emphasis on human-centric production. Characterized by the sophisticated integration of technologies such as AI and IoT into manufacturing processes, Industry 5.0 enhances the interaction between humans and machines. This approach is aimed at creating a more holistic and sustainable approach to manufacturing, where advanced technologies are not only utilized for efficiency but also to value and augment the role of human workers. The primary aim of Industry 5.0 is to forge a more equitable and sustainable future, focusing on the well-being of workers and the environment (Xu et al., 2021).

Industry 5.0, evolving from its predecessor, Industry 4.0, is not just a technological upgrade but a transformative shift that brings a multitude of benefits to businesses and society. This latest industrial phase, characterized by the integration of advanced technologies like AI and IoT, focuses on human-centered production, aiming to improve productivity, quality, flexibility, safety, sustainability, and cost-effectiveness in manufacturing. A study by Maddikunta et al. (2022) highlights these wide-ranging benefits, emphasizing how Industry 5.0 blends technical sophistication with human ingenuity for a more balanced industrial ecosystem.

A pivotal yet often overlooked aspect of Industry 5.0 is its strong focus on ergonomics as an integral part of its human-centered approach. Ergonomics involves designing workspaces and equipment that align with the capabilities and limitations of workers, aiming to maximize safety, comfort, and productivity. This ergonomic focus in Industry 5.0 is crucial for enhancing the work environment and ensuring worker well-being.

In the context of Industry 5.0, advanced technologies like robotics and automation play a key role in automating hazardous or physically demanding tasks. This automation significantly reduces the risk of injuries or strains for workers, as highlighted by Coronado et al. (2022). Additionally, the principles of ergonomic design are applied to improve the physical and cognitive well-being of workers, as detailed in the research by Lu et al. (2022), emphasizing the importance of ergonomic interventions in modern manufacturing setups.

Therefore, this study aims to conduct an ergonomic analysis in human-machine workplaces within the framework of Industry 5.0. The focus is on creating value for individuals involved in various production processes, with a particular emphasis on simulation-based design methods. This approach will explore the potential of ergonomic designs in enhancing the efficiency and safety of human-machine interactions in industrial settings.

2. Theoretical background

As industries evolve and embrace the advancements of Industry 5.0, the role of ergonomics in shaping modern workplaces becomes not just essential, but fundamental to the well-being and improvement of workers. Ergonomics, often referred to as human factors engineering, is crucial in enhancing interactions between humans and the systems they operate within. This scientific discipline, deeply rooted in ensuring worker comfort and safety, has gained heightened importance in the era of Industry 5.0. In this advanced industrial landscape, the integration of ergonomics transcends traditional workplace design; it is now essential in optimizing human-machine interactions and improving the cognitive and physical aspects of work.

In this conceptual framework, we begin by exploring the evolution of ergonomics from its inception to its current role in Industry 5.0. This journey highlights the development of various tools and methodologies, such as RULA and the use of inertial sensors, designed to measure ergonomic risks and enhance workplace design. As we delve into the challenges of ergonomics in the context of Industry 5.0, we recognize the increasing complexity of human-machine collaboration and the need for more advanced ergonomic solutions. These challenges pave the way for future directions in ergonomic research and practice, focusing on adaptive and intelligent systems that can anticipate and mitigate risks in real-time, ensuring a harmonious and productive coexistence of humans and advanced technologies in the workplace. This exploration not only reflects the historical significance of ergonomics but also underscores its critical role in the future of industrial development.

2.1. Definition, importance and evolution of Ergonomics until Industry 5.0

Ergonomics is the scientific discipline concerned with understanding the interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to advance human well-being and overall system performance (Association International Ergonomics, 2003; Dul et al., 2012; Karwowski, 2006) It focuses on designing work environments tailored to the physical and cognitive capabilities and limitations of employees (Kroemer Elbert et al., 2018). This includes interventions at macro (organizational, systems) levels as well as micro (individual), where workers are given the opportunity and power to use their knowledge to address ergonomic problems relating to their own working activities (Hendric & Kleiner, 2002). Ergonomics has played essential roles in the technical cooperation activities of the International Labour Organization (ILO) in occupational safety and health in industrially developing countries (Kawakami, 2005). Furthermore, ergonomic factors are of great importance, not only in relation to the worker's own health and safety but also in other aspects associated with production (Olsen, 2007). It is also important in identifying risks, developing and applying reliable assessment tools, methodologies, and techniques, and defining preventive recommendations to help reduce exposure risks, improve work organization, and design workplaces (Hignett & McAtamney, 2000). Additionally, ergonomics is indispensable in developing action aimed towards environmental preservation and the development of sustainable products, processes, and service designs (Radjiyev et al., 2015). Moreover, ergonomics is helpful in both the prevention of occupational diseases and the promotion of health (Buckle & Jason Devereux, 2002).

Ergonomics has undergone significant evolution from the era of traditional manufacturing through to Industry 4.0 and now Industry 5.0, a transformation largely driven by technological advancements. These advancements have notably influenced ergonomic approaches within the industry, especially with the emergence of Industry 4.0. The integration of virtual reality and digital human modeling has gained traction for ergonomic assessments in industrial product development, offering new avenues for evaluating and optimizing workplace ergonomics (da Silva et al., 2022). Additionally, the concept of "Cybergonomics" has been proposed to address the ergonomic challenges posed by Industry 4.0 technologies, emphasizing the need to adapt ergonomic principles to the evolving technological landscape (Pouyakian, 2022). Furthermore, the use of advanced digital technologies has enabled the redesign of automatic machines with a human-centric approach, focusing on enhancing worker well-being and factory productivity simultaneously (Grandi et al., 2022). Augmented reality principles have also been employed for process management of ergonomic workplaces, highlighting the integration of data analytics and VR/AR technology for ergonomic optimization (Holoči et al., 2022). Moreover, the evolution of ergonomics risk assessment methods has been driven by the need to prevent work-related musculoskeletal disorders (WMSDs) in the context of Industry 4.0, necessitating the transformation and adaptation of assessment methods with advanced technology-based approaches (Rawan et al., 2022). Overall, the Industry 4.0 concept has paved the way for the development and implementation of advanced industrial tools of ergonomics, signifying a paradigm shift in ergonomic approaches within the industrial domain (Gašová et al., 2017).

The integration of ergonomics in smart manufacturing environments under Industry 5.0 is pivotal for fostering human-machine collaboration and designing human-centered automation systems. As smart manufacturing evolves, the role of ergonomics becomes increasingly significant in ensuring the well-being, safety, and productivity of workers. The convergence of digital technologies, cyber-physical systems, and human-centric automation presents new opportunities for integrating ergonomics into the manufacturing landscape.

Ergonomics in Industry 5.0 encompasses the design of adaptive and responsive work environments that prioritize human well-being and performance. The utilization of digital twins, advanced analytics, and real-time monitoring enables the creation of accurate simulations of work environments, facilitating the analysis and optimization of ergonomic factors (Thoben et al., 2017). This integration allows for the dynamic adaptation of manufacturing processes to accommodate human needs and capabilities, thereby enhancing worker well-being and productivity.

Among these technologies mention, inertial sensors play a crucial role in monitoring and improving movement and posture at work within smart manufacturing environments. By integrating inertial sensors with digital twins, it becomes feasible to create human digital twins based on personalizable kinematic body models, allowing for precise movement and posture monitoring and ergonomic assessments in industrial settings (Wang et al., 2021).

The future of ergonomics in smart manufacturing and Industry 5.0 is poised to advance through the seamless integration of human-machine collaboration and the design of human-centered automation systems. The development of adaptive and responsive work environments, facilitated by digital twins and inertial sensors, will enable the creation of personalized ergonomic interventions and design solutions tailored to individual workers. This will lead to the optimization of workplace ergonomics, enhancing worker well-being, safety, and productivity within the smart manufacturing landscape.

2.2. Tools and Methods for Improving Ergonomic Well-being

The key tools and methods used in industrial ergonomics encompass a wide array of technological and ergonomic solutions aimed at enhancing workplace safety, comfort, and efficiency. Adjustable workstations stand as a fundamental tool, allowing workers to customize their work environment to suit their individual ergonomic needs, thereby contributing to improved comfort and reduced risk of musculoskeletal disorders (Swinton et al., 2017). Ergonomic tools such as exoskeletons have gained prominence for their ability to reduce physical strain during lifting tasks, thereby enhancing safety and comfort in industrial settings (Rupal et al., 2017). Motion analysis software, such as the Open Motion Planning Library, has been instrumental in evaluating and optimizing workplace ergonomics, particularly in the design and assessment of ergonomic solutions aimed at reducing physical strain on workers (Şucan et al., 2012). Furthermore, ergonomic risk assessment tools like the Rapid Upper Limb Assessment (RULA) have been combined with inertial motion capture technology to provide more sensitive evaluations of work routines, thereby contributing to improved safety and comfort at work (Blume et al., 2021).

Effective ergonomic design is essential for enhancing productivity and reducing injuries and musculoskeletal disorders in the workplace. Incorporating ergonomic principles, such as adjustable workstations, ergonomic tools, and motion analysis software, can create work environments that promote worker well-being and efficiency. For example, adjustable workstations allow employees to customize their workspaces, reducing physical strain and discomfort, thereby enhancing productivity and reducing the risk of musculoskeletal disorders (Qutubuddin et al., 2014). Similarly, ergonomic tools like exoskeletons have been shown to reduce physical strain during lifting tasks, contributing to improved safety and comfort, ultimately enhancing productivity. Motion analysis software enables the evaluation and optimization of workplace ergonomics, leading to improved safety and comfort by identifying and addressing ergonomic concerns, consequently enhancing overall efficiency.

Several successful case studies and examples demonstrate the positive impact of ergonomic implementations in various industries. For instance, a study on participatory ergonomics in the footwear industry demonstrated that the implementation of ergonomic interventions led to improved occupational safety and health, as well as increased productivity (Sukapto et al., 2019). Additionally, a case study on the effect of office ergonomics in Nigeria highlighted the importance of ergonomic theory in enhancing office workers' productivity ("Effect of Office Ergonomics on Office Workers' Productivity in the Polytechnics, Nigeria", (Baba et al., 2021)). Furthermore, the use of scientific ergonomic programs in a chemical plant resulted in quality improvement and increased productivity (Hadidi et al., 2019). These examples underscore the significant role of ergonomics in enhancing worker well-being, safety, and productivity across diverse industrial settings.

Therefore, effective ergonomic design, facilitated by tools and methods such as adjustable workstations, ergonomic tools, and motion analysis software, is instrumental in enhancing productivity and reducing injuries and musculoskeletal disorders in the workplace. The successful implementation of ergonomic interventions in various industries further emphasizes the positive impact of ergonomics on worker well-being and organizational performance.

Considering the significant advantages that effective ergonomic design brings, it is crucial first to utilize tools that help analyze the potential musculoskeletal risks present in the workplace. This initial step is essential for identifying specific areas where ergonomic interventions can be most beneficial. In the field of occupational ergonomics, a variety of specialized tools are used to assess musculoskeletal risks, each with its unique focus. Among the most common, the REBA (Rapid Entire Body Assessment) and RULA (Rapid Upper Limb Assessment) methods are essential for evaluating postural risks across the entire body and in the upper limbs, respectively. The NIOSH method is widely used to establish safe limits for lifting tasks. Meanwhile, OWAS (Ovako Working Posture Analyzing System) concentrates on analyzing work postures. Additionally, the Snook and Ciriello method determines load limits for lifting and movements, while GINSH specializes in healthcare, assessing tasks such as patient handling. The Job Strain Index (JSI) and Occupational Repetitive Actions (OCRA) are key for repetitive tasks, particularly in the upper extremities. The Fanger method assesses thermal comfort in the work environment, and the Moore and Garg Strain Index, along with the Lehto and Landry method, focus on manual tasks and tool design to reduce fatigue and injury risk. These tools are fundamental for a comprehensive evaluation of ergonomic risks in various work environments.

In a scientific article advocating for the use of the RULA (Rapid Upper Limb Assessment) method in lean production lines, it's important to highlight its distinct advantages. RULA stands out for its ability to provide quick and effective assessments of ergonomic risks associated with upper limb disorders, a common concern in lean manufacturing environments. Its simplicity and ease of use allow for rapid evaluations without significant disruption to production processes (Figure 1).

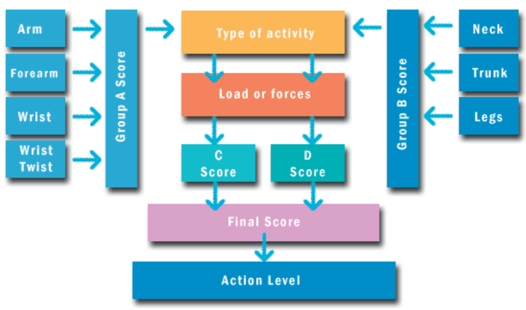


Figure 1. Process of Obtaining the RULA Score. Source: Diego-Mas, 2023.

This method's focus on upper body postures, including the neck, trunk, and upper limbs, makes it particularly relevant for tasks involving repetitive motions or prolonged static postures, which are prevalent in lean production settings. RULA's scoring system helps in prioritizing interventions by identifying high-risk tasks, thus facilitating targeted ergonomic improvements (Figure 2).

Score	Level	Action
1 or 2	1	Acceptable Risk
3 or 4	2	Task changes may be required; further study is recommended
5 or 6	3	Task redesign is required
7	4	Urgent changes in the task are required

Figure 2. Action levels according to the final score obtained. Source: Diego-Mas, 2023

This proactive approach not only enhances worker safety and comfort but also contributes to increased productivity and quality, aligning well with the principles of lean manufacturing. By integrating RULA into regular ergonomic assessments, lean production lines can significantly reduce the incidence of work-related musculoskeletal disorders, leading to a healthier, more efficient, and sustainable work environment.

2.3. Industry 5.0 Ergonomics: Challenges and applications

The integration of ergonomic principles in highly automated and technologically advanced manufacturing settings presents several potential challenges and limitations. These include the need to adapt ergonomic solutions to rapidly evolving technologies, the complexity of human-machine interfaces, and the potential for increased mental and cognitive demands on workers due to automation. Additionally, the implementation of ergonomic interventions in such environments may face resistance due to the lack of awareness, skills, and training in ergonomic techniques, as well as the unwillingness to change existing organizational cultures (Gualtieri et al., 2020). Furthermore, the fragmented and cyclic nature of manufacturing projects, unavailing communication between project participants, and the high costs associated with implementing ergonomic solutions pose significant challenges (Ahmed & Sobuz, 2020).

To overcome these challenges, policy implications and continuous learning and adaptation are essential. Policy initiatives should focus on raising awareness, providing training in ergonomic techniques, and fostering a culture of continuous improvement and adaptation to technological advancements. Additionally, the development of human-centered collaborative workstations and the integration of participatory ergonomics interventions can address the physical ergonomics of operators and improve production efficiency (Gualtieri et al., 2020). Furthermore, the use of digital twins and inertial sensors can facilitate real-time monitoring and optimization of ergonomic parameters, enabling the creation of adaptive and responsive work environments that prioritize worker health and performance (Colim et al., 2021). Collaboration between academia, industry, and government can provide insights and potential solutions from a holistic view, addressing barriers and facilitating the adoption of ergonomic interventions (Hoffmann et al., 2023).

The challenges and limitations in implementing ergonomic solutions in Industry 5.0 demand a comprehensive, multi-faceted approach. This involves not only addressing policy implications and fostering an environment of continuous learning and adaptation but also developing human-centered collaborative workstations. Such workstations are designed to be in harmony with human needs and capabilities, ensuring both comfort and efficiency. Additionally, integrating advanced technologies for real-time monitoring and optimization of ergonomic parameters is crucial. This integration can leverage tools such as wearable sensors and AI-driven analytics to provide immediate feedback and proactive adjustments, ensuring that ergonomics is not just a static feature but a dynamic aspect of the workplace, continuously evolving with the workers' needs and the production processes.

This approach to ergonomics, which combines policy, technology, and continuous improvement, sets the stage for exploring real-world applications. In various industries, case studies demonstrate how effectively implemented ergonomic solutions can lead to significant improvements in worker well-being, productivity, and overall organizational performance. These real-world examples serve as both a testament to the benefits of ergonomic integration in Industry 5.0 and as a guide for future implementations.

In the case study "Human–Robot Interaction for Improving Fuselage Assembly Tasks," the authors present a case study regarding the reorganization of the working activity carried out in a workstation in which a composite fuselage panel is assembled. The study aims to demonstrate, by means of simulation tools, that advantages can be achieved in the aerospace industry through human-robot interaction, improving ergonomics and efficiency (Laudante et al., 2020).

The case study "Virtual Reality and Digital Human Modeling for Ergonomic Assessment in Industrial Product Development" focuses on the application of virtual reality and digital human modeling for ergonomic assessment in industrial product development. The study provides a comprehensive review of patents and literature, highlighting the significance of these technologies in enhancing ergonomic assessments and design processes (da Silva et al., 2022).

In the case study "Application of Virtual Reality to Perform Ergonomic Risk Assessment in Industrialized Construction: Experiment Design," the authors explore the application of virtual reality to perform ergonomic risk assessment in industrialized construction. The study presents an experiment design that demonstrates the potential of virtual reality in assessing ergonomic risks in construction settings, emphasizing the practical application of this technology (Barkokebas et al., 2020).

These case studies illustrate the successful integration of ergonomic principles into Industry 5.0 environments, highlighting how leveraging advanced technologies like human-robot interaction, virtual reality, and digital human modeling can significantly improve ergonomics, efficiency, and safety in industrial settings. Key lessons include the importance of using simulation tools, patents, and literature for advancing ergonomic assessments and design processes. Best practices identified from these studies point towards the use of advanced technologies in enhancing human-robot interactions and ergonomic design processes, ultimately leading to more efficient and ergonomically sound workplaces in Industry 5.0 environments. Building on these advancements, the integration of digital twins has emerged as a particularly powerful tool in this realm.

2.4. Advancing Ergonomics in Industry 5.0: Digital Twins, Sensors, and Future Directions

The role of digital twins in simulating and optimizing ergonomic work environments marks a significant step forward in this field. Defined as virtual replicas of physical products or systems, continuously updated with real-time data, digital twins enable accurate simulations of work environments. This capability allows for comprehensive analysis and optimization of ergonomic factors. By employing digital twins, it becomes feasible to model and assess the impact of various ergonomic interventions and design changes on worker well-being and productivity. This innovative approach not only advances future ergonomics but also enhances the integration of ergonomic considerations in workplace design. The utilization of digital twins in co-simulation environments, particularly when combined with virtual reality software, has opened new avenues for ergonomic analysis and optimization, offering a glimpse into the future of workplace design and worker well-being.

Inertial sensors play a crucial role in monitoring and improving movement and posture at work. These sensors, such as inertial measurement units (IMUs), have been utilized to estimate orientation and assess human movement and posture with high accuracy and repeatability. By integrating inertial sensors with digital twins, it becomes feasible to create human digital twins based on personalizable kinematic body models, allowing for the synthesis of sensor data and the estimation of sensor-dependent algorithm performance in co-simulations. This approach enables the analysis of gait event estimation and provides valuable insights into ergonomic assessments of human movement and posture in industrial settings.

The convergence of digital twins and inertial sensors holds significant promise for advancing the ergonomics of the future. By harnessing the capabilities of digital twins to create accurate simulations of work environments and integrating inertial sensors for precise movement and posture monitoring, it becomes possible to develop personalized ergonomic interventions and design solutions tailored to individual workers. This can lead to the optimization of workplace ergonomics, enhancing worker well-being, safety, and productivity. Furthermore, the use of digital twins and inertial sensors can facilitate the real-time assessment and optimization of ergonomic parameters, contributing to the creation of adaptive and responsive work environments that prioritize worker health and performance.

Emerging trends and future research directions in ergonomics, particularly in relation to Industry 5.0, encompass a wide array of topics and potential areas for exploration. The integration of advanced technologies, such as virtual reality, digital human modeling, and human-robot interaction, presents new opportunities for advancing ergonomic design and implementation in industrial settings. Additionally, the application of digital twins, inertial sensors, and adaptive automation assembly systems offers potential avenues for enhancing workplace ergonomics and human-machine collaboration.

Upcoming technological advancements are expected to shape the future of ergonomic design and implementation in industrial settings. The utilization of digital twins and virtual reality for ergonomic assessment and design processes is anticipated to become more prevalent, enabling the creation of accurate simulations of work environments and the optimization of ergonomic factors. Furthermore, the integration of inertial sensors with digital twins and human-robot interaction technologies holds promise for precise movement and posture monitoring, as well as the development of adaptive and responsive work environments that prioritize worker health and performance. The application of adaptive automation assembly systems is also expected to play a significant role in advancing ergonomic design, offering opportunities for the development of human-centered automation solutions tailored to individual workers.

Overall, the future of ergonomics in Industry 5.0 is poised to be shaped by the continued integration of advanced technologies, the development of adaptive and responsive work environments, and the prioritization of worker well-being and performance. Research in these areas is expected to contribute to the advancement of workplace ergonomics, safety, and efficiency in the evolving industrial landscape.

3. Methods

To address the ergonomic analysis in the context of Industry 5.0, this article adopts a detailed methodological process as illustrated in the attached Figure 3. The analysis begins with an exploration of Industry 5.0, focusing on one of its fundamental pillars: the human-centered approach. Within this framework, ergonomics emerges as a key area for development, particularly in enhancing well-being and safety within the human-centered approach. Ergonomics presents various challenges and applications, and as discussed in the theoretical section, we have observed numerous challenges that have evolved in recent years. However, one of the major limitations in improving ergonomics lies in the integration and utilization of advanced technologies. The use of digital twins and inertial sensors, for instance, can facilitate real-time monitoring and optimization of ergonomic parameters. This enables the creation of adaptive and responsive work environments that prioritize worker health and performance, aligning with the principles of Industry 5.0. This methodological approach aims to bridge the gap between traditional ergonomic practices and the advanced capabilities offered by Industry 5.0, offering a comprehensive view of the current state and potential of ergonomics in modern industrial settings.

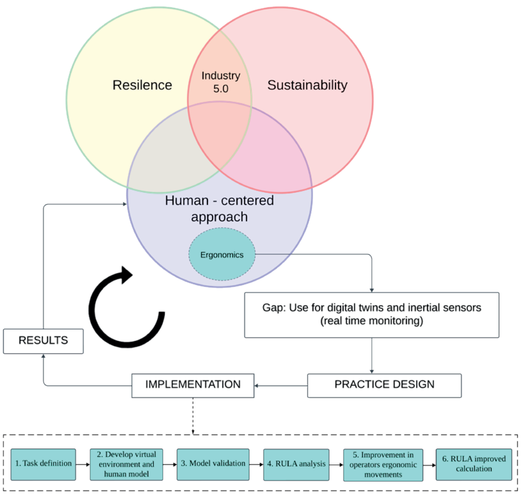


Figure 3. Methodological process model.

To achieve this, a practice design focused on a lean manufacturing line and its implementation has been carried out. The objective is to obtain results through inertial sensors that allow for the generation of more knowledge and continue to feed the development of ergonomics within Industry 5.0. This practical application not only demonstrates the effectiveness of integrating advanced technologies in ergonomic assessments but also contributes to the evolving body of knowledge in ergonomics, ensuring that ergonomic practices remain relevant and effective in the ever-advancing industrial landscape.

To conduct the ergonomic analysis detailed in this study, the following practice design, resources, including equipment and software were essential.

3.1. Practice design

The production line analyzed is the FAS-200, a flexible and compact packaging system developed by SMC[1] for educational purposes. This system, which integrates technologies from the automation industry, consists of four independent stations with integrated control. It simulates the assembly of a car, simplifying operations to facilitate the tasks performed by operators on the line. Each station in the FAS-200 line is capable of either automatic or manual operation, and for this study, the stations were set to function automatically. The FAS-200 line is designed to offer professional training that mirrors industrial realities, with all components standardized for industry use.

In this educational assembly line, the tasks involve assembling independent pieces that represent various car parts, such as the car structure, engine, roof, and wheels. The process is designed to mimic real-world car assembly but in a more simplified manner, emphasizing the interaction between humans and machines. The assembly line offers the possibility of creating four distinct car models, differentiated by the color of the roof (green, black, red, or white), as visualized in Figure 4.

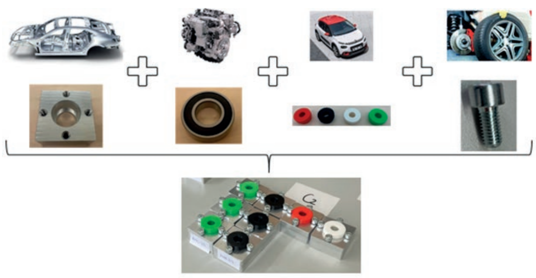


Figure 4. Visualization of Parts and Assemblies on the Assembly Line.

The layout of the workstation line, as depicted in Figure 5, includes four distinct stations, each contributing to a different stage of the assembly process. The first station involves inserting a base, which serves as the foundation for the subsequent assembly stages. At this stage, the car structures are loaded and inserted into the line for initial checks. The second station involves picking up these car structures and positioning them onto the main base. The third station's task is to load engines, preparing them for mounting. Finally, the fourth station is

[1] SMC: Japanese manufacturer in pneumatic and electrical automation solutions.

responsible for the final assembly, where the engine is picked up, checked, and assembled with the rest of the car components, assisted by an automatic process. The final step involves manually mounting the roof and wheels, completing the assembly through a combination of manual and automated processes.

Figure 5. Representation of the FAS-200 Assembly line.

3.2. Implementation

In this study, two distinct but complementary approaches are employed for ergonomic analysis. The first approach utilizes Tecnomatix Process Simulate Human software, a powerful tool for creating digital twins and conducting ergonomic assessments. This software allows for the sizing of human figures to match worker populations and tests designs for multiple factors, including injury risk, user comfort, reachability, line of sight, energy expenditure, fatigue limits, and other crucial human parameters. The use of Process Simulate Human offers significant cost and time savings by enabling improvements in product quality and process feasibility early in the product lifecycle. It integrates human factors and ergonomics seamlessly into the planning, design, and validation stages, leveraging classic ergonomic and human factor assessment techniques along with the latest visualization and simulation technologies (Siemens, 2024) (Figure 6).

The second approach in this study involves the use of the MTw Awinda, a second-generation wireless inertial-magnetic motion tracker by Xsens (Bellusci et al., 2013), to synchronize with the Tecnomatix Process Simulate Human environment. This method offers a hands-on, real-time analysis of ergonomic factors, providing a dynamic and comprehensive ergonomic assessment. The MTw Awinda system is known for its highly accurate orientation tracking in a non-intrusive setup, making it ideal for detailed ergonomic studies.

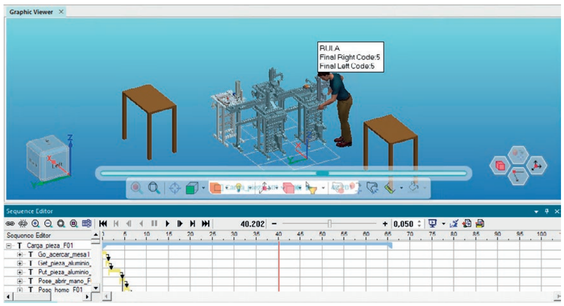


Figure 6. Ergonomic Simulation in Tecnomatix of FAS200 SMC production line.

By integrating the MTw Awinda sensors with the virtual environment developed in Tecnomatix Human Process Simulate, it is possible to achieve a synchronization that allows for an in-depth evaluation of the postures adopted by operators during the assembly process. This practical approach complements the digital twin analysis by providing real-world data on human movement and posture. The MTw Awinda system's flexibility and reliability make it a valuable tool for capturing human motion in a variety of applications, even in challenging environments. Its performance has been validated in various scenarios, including sports and gaming movements, as well as walking and running under magnetic distortions. Importantly, the capabilities of the MTw Awinda system are also valid for industrial cases, making it an effective solution for ergonomic assessments in manufacturing and other industrial settings

This integration of advanced inertial sensors with digital twin technology represents a significant step forward in ergonomic assessment, allowing for a more nuanced understanding of how operators interact with their work environment. The results from the MTw Awinda system provide critical insights into human motion, enhancing the overall quality and applicability of the ergonomic analysis where accurate motion tracking is crucial (Figure 7 and Figure 8).

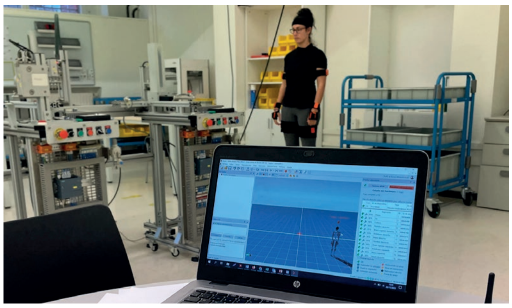


Figure 7. Integrating inertial sensors into implementation (initial phase).

Figure 8. Integrating inertial sensors into implementation (final phase).

The Rapid Upper Limb Assessment (RULA) method is employed in both approaches to evaluate the risk factors associated with musculoskeletal disorders (MSDs) in the upper extremities. RULA, a widely recognized ergonomic assessment tool, is instrumental in assessing and identifying potential ergonomic hazards in various tasks or job settings. The detailed steps of this ergonomic analysis, including the use of Tecnomatix Human Process Simulate, inertial sensors, and the RULA method, are illustrated in Figure 9.

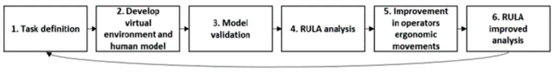


Figure 9. Flow diagram applied in ergonomic analysis implementation.

This dual approach, combining the digital twin model with real-time sensor data, provides a holistic view of ergonomic risks and opportunities, ensuring a thorough and effective ergonomic assessment in line with the latest industry standards.

4. Results

After meticulously defining the work tasks, a series of simulations were conducted to analyze the operator's movements and their interactions with the workstations. These simulations were grounded in various ergonomic studies, focusing on the operator's posture and movement efficiency within the assembly line environment (Figure 10). The primary tool used for these analyses was the Rapid Upper Limb Assessment (RULA) method, which provided a detailed evaluation of the ergonomic risks associated with the operator's tasks.

The RULA method, known for its focus on static postures, allowed us to pinpoint the most critical postures at each workstation. Through these evaluations, we identified six postures that posed the highest risk for musculoskeletal disorders, underscoring the need for immediate ergonomic interventions as can be seen by the preliminary results in the following table.

Figure 10. Static example posture in first workstation.

Table 1. RULA score summary of the critical posture of each station.

	Posture 1	Posture 2	Posture 3	Posture 4	Posture 5	Posture 6
	Insert Base	Picking up car structures and position in main base	Load Engine and prepare for mounting	Final automotic assembly	Manually mounted roof	Manually mounted wheels
Arm	4	4	4	1	2	2
Forearm	1	1	1	1	1	3
Wrist	3	2	3	2	2	3
Wrist Twist	2	1	1	1	1	1
Group A Score	**5**	**4**	**5**	**2**	**3**	**4**
Type of Activity	1	1	1		1	1
C score	**6**	**5**	**6**	**2**	**4**	**5**
Neck	3	3	3	2	2	3
Trunk	3	3	2	2	2	3
Legs	1	1	1	1	1	1
Group B Score	**4**	**4**	**3**	**2**	**2**	**4**
Loads or forces						
D score	**4**	**4**	**3**	**2**	**2**	**4**
RULA final score	**6**	**5**	**5**	**2**	**3**	**5**

The RULA reports, generated from each simulation, offered valuable insights into the ergonomic aspects of the assembly line. These reports, presented a comprehensive view of the operator's postural alignment and potential risk factors for musculoskeletal disorders. The RULA scores, derived from these reports, were instrumental in identifying specific areas where ergonomic improvements were necessary. A summary of the findings and the necessary actions for the six analyzed postures is detailed in the following table:

Table 2. Necessary actions for the analyzed postures.

Posture	RULA score	Ergonomic Risk Level	Recommended action
Station 1	6	3 (High risk)	Task redesign is required
Station 2	5	3 (High risk)	Task redesign is required
Station 3	5	3 (High risk)	Task redesign is required
Station 4	2	1 (Acceptable risk)	Task changes may be required: further study is recommended
Station 5	3	2 (Moderate risk)	No immediate action required, continue monitoring
Station 6	5	3 (High risk)	Task redesign is required

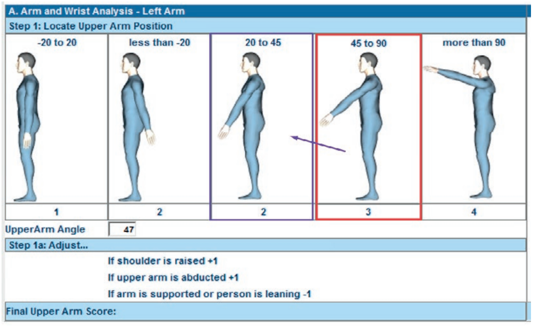
This preliminary analysis highlights that out of the six positions evaluated, four require task redesign due to high ergonomic risks. One position suggests that task changes may be required, with further study recommended to better understand the specific ergonomic interventions needed. Notably, posture 4 presents an acceptable risk level, indicating that, for the time being, no immediate ergonomic interventions are necessary, although continuous monitoring is advised to ensure that the risk level remains controlled.

These findings emphasize the critical need for targeted ergonomic improvements to mitigate the identified risks and enhance the overall safety and well-being of the operators on the assembly line.

These findings emphasize the critical need for targeted ergonomic improvements to mitigate the identified risks and enhance the overall safety and well-being of the operators on the assembly line. Considering the pivotal results from these RULA analyses, the study effectively guided the ergonomic enhancement of the assembly line. By closely examining the RULA scores and the associated ergonomic risk factors, were planned and implemented targeted interventions aimed at improving the overall quality of the assembly line. Part of these interventions involved a comprehensive redesign of the workstations, adjusting the height, reach, and orientation of the workstations to adapt them to the ideal ergonomic setup. This redesign minimized the need for forced postures, excessive reaching, and repetitive movements that were detected in the initial analyses. This comprehensive approach illustrates our commitment to not just identifying potential ergonomic issues but actively addressing them through thoughtful and effective changes, ultimately fostering a healthier and more productive work environment.

The outcomes of these ergonomic improvements, as reflected in the RULA reports, can be seen in Figure 11, Figure 12 and Figure 13. This figure illustrates the before-and-after scenarios of the ergonomic interventions, showcasing the tangible improvements made in reducing ergonomic risks and enhancing operator comfort. The successful application of these ergonomic principles and the subsequent positive results underscore the importance of integrating ergonomic assessments, like RULA, into the design and optimization of industrial work environments.

Building upon this foundation, the initial phase of the analysis focused on enhancing specific body areas as seen in Group A (Arm, Forearm, and Wrist), detailed in the "RULA Arm and Wrist Analysis" presented in the subsequent figure. Furthermore, attention was also given to Group B (Neck, Trunk, and Legs), aiming to address and improve postures related to these areas, as will be elaborated in the following figures. This stepwise approach ensured a comprehensive assessment and improvement of operator postures, starting with individual limbs and progressing to include the entire body, effectively mitigating ergonomic risks across all aspects of the work environment.



Before improvements ☐, After improvements ☐

Figure 11. Rula Arm and Wrist comparison in Posture 3.

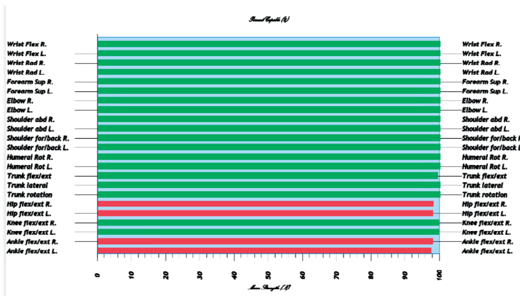


Figure 12. RULA static analysis.

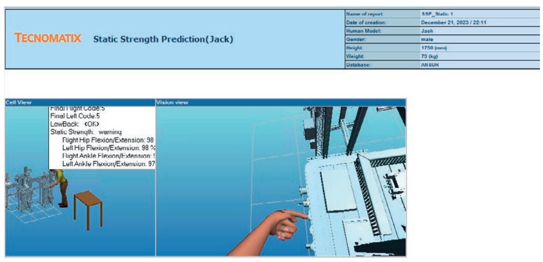


Figure 13. RULA general results vision in station 1.

Following the implementation of the targeted ergonomic improvements in the assembly line, a significant reduction in the RULA (Rapid Upper Limb Assessment) index was observed (see Figure 14). This substantial decrease in the RULA index is a clear indicator of the effectiveness of the ergonomic interventions that were put into place.

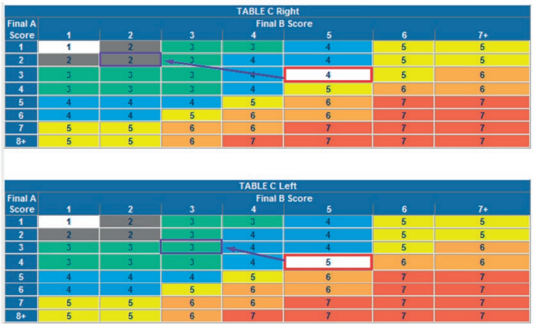


TABLE C Right							
Final A Score	Final B Score 1	2	3	4	5	6	7+
1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

TABLE C Left							
Final A Score	Final B Score 1	2	3	4	5	6	7+
1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

Before improvements ☐, After improvements ☐

Figure 14. RULA results comparison before and after improvements.

The comprehensive summary of the final values for each posture, including the C Score, D Score for each group, and the final RULA value, is presented in the following table to showcase the percentage improvement in each case. This representation allows for a detailed graphical visualization of the contribution and impact of the ergonomic interventions across each figure, highlighting the effectiveness of the implemented improvements.

Table 3. Summary of RULA improvement comparison in percentage.

	Posture 1	Posture 2	Posture 3	Posture 4	Posture 5	Posture 6
C score	6	5	6	2	4	5
D score	4	4	3	2	2	4
RULA final score	**6**	**5**	**5**	**2**	**3**	**5**
C score	4	4	4	2	2	3
D score	3	3	2	2	2	3
RULA final score	**3**	**3**	**3**	**2**	**2**	**3**
RULA REDUCTION	**50,00%**	**40,00%**	**40,00%**	**0,00%**	**33,33%**	**40,00%**
IMPROVED POSTURES AVERAGE						**40,67%**

Before improvements
After Improvements

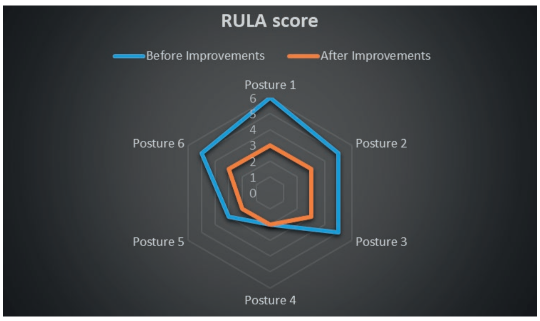


Figure 15. Summary of RULA comparison analysis.

The reduction in the RULA score is particularly noteworthy, as it not only reflects a comprehensive improvement in the operator's working conditions but also signifies a shift from four operations initially classified as high risk to four operations now deemed to be at moderate risk, and two operations considered to be at an acceptable risk level. The RULA assessment method, which evaluates critical factors such as posture, muscle use, and force exertion in determining the risk of musculoskeletal disorders, has been instrumental in achieving this 40% reduction. This improvement implies that operators are now working in a more ergonomically favorable environment, significantly lowering the risk of strain and injury and enhancing workplace safety and comfort.

This improvements obtained can be attributed to several key changes made in the assembly line. These may include adjustments to workstation design, such as optimizing the height and reach distances, introducing ergonomic tools and equipment to reduce physical strain, and modifying work procedures to allow for more natural body movements. Additionally, training sessions for operators on proper ergonomic practices likely contributed to this positive outcome.

The impact of these changes extends beyond just the reduction in RULA scores. It likely translates into better overall operator well-being, including reduced fatigue, lower risk of long-term musculoskeletal issues, and improved job satisfaction. Furthermore, these ergonomic enhancements can lead to increased productivity and efficiency, as operators are able to work more comfortably and effectively.

In conclusion, the more than 40% reduction in the RULA index at each workstation is a testament to the successful integration of ergonomic principles into the assembly line. This achievement not only enhances the immediate working conditions for the operators but also sets a precedent for future ergonomic practices in similar industrial settings.

5. DISCUSSION

Industry 5.0 represents a paradigm shift in manufacturing, where the focus is not solely on technological advancements and automation but also on the human aspect of production (Agote-Garrido et al., 2023). This human-centered approach emphasizes the integration of advanced technologies to enhance human capabilities, streamline efficiency, and boost overall productivity. In this context, the well-being of workers and the sustainability of the environment are given paramount importance. By incorporating ergonomic principles into the design of workspaces, tools, and equipment, Industry 5.0 aims to create a safer, more comfortable, and productive environment for workers. This approach recognizes that the health and comfort of workers are directly linked to their productivity and the quality of their work.

Ergonomics in Industry 5.0 goes beyond traditional workplace safety measures (Coronado et al., 2022). It involves a holistic view of the worker's experience, considering factors such as physical strain, mental stress, and the potential for long-term health issues. This perspective is crucial in a landscape where technology and human labor are increasingly intertwined. By prioritizing ergonomics, Industry 5.0 seeks to ensure that technological advancements do not come at the cost of worker health and well-being (Welfare et al., 2019). Instead, these advancements are used to create a more humane and sustainable working environment, where the physical and psychological needs of workers are addressed.

In line with these principles, a specific work methodology has been developed in this study to simulate assembly tasks and evaluate the ergonomic requirements of the work (Donmezer et al., 2023). This methodology is designed to optimize the interaction between human and machine, ensuring that workers can perform their tasks efficiently without compromising their health or safety. The use of tools like digital twins and inertial sensors in this methodology allows for a detailed analysis of work processes and the identification of potential ergonomic risks. This approach not only benefits the workers by improving their working conditions but also has significant potential for transfer to the broader industrial fabric.

The implications of this methodology are far-reaching (Calzavara et al., 2023). By demonstrating how ergonomic considerations can be seamlessly integrated into the manufacturing process, it sets a precedent for future industrial practices. This approach aligns with the goals of Industry 5.0, where the enhancement of human work through technology is balanced with the imperative to maintain and improve worker well-being. As industries continue to evolve, this human-centered approach to ergonomics will be crucial in shaping sustainable, efficient, and worker-friendly manufacturing environments.

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