Advances in Production Engineering & Management
Volume 19 | Number 3 | September 2024 | pp 333–346
https://doi.org/10.14743/apem2024.3.510
ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

Enhancing workplace safety and ergonomics with motion capture systems: Present state and a case study

Vujica Herzog, N.[a,*], Buchmeister, B.[a], Jaehyun, P.[b], Kaya, Ö.[c]

[a]University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia
[b]Konkuk University, Department of Industrial Engineering, Seoul, Republic of Korea
[c]University of Uşak, Faculty of Fine Arts, Uşak, Turkey

A B S T R A C T

A motion capture system (MoCap) records and tracks the real-time movements of objects or people, generating data that can also be used for ergonomic analysis. Using specialised cameras and sensors, these systems translate movements into digital data that can animate figures or objects in a digital environment. While they are widely used in industries such as film, video games, sports, virtual reality and biomechanics, MoCap systems can also be used in the ergonomic design of workplaces. These systems allow researchers to analyse human movements, identify risks such as repetitive movements, awkward postures or excessive forces and develop solutions to improve safety, comfort and performance. The collected data helps to optimise workplace design, products and processes, reduce musculoskeletal disorders and improve well-being. Recent advancements have made motion capture systems highly sophisticated and capable of recognising subtle movements and expressions with exceptional precision. This paper consists of two parts: a concise literature review and a case study. The literature review explores the application of advanced human motion capture technologies in manufacturing and highlights their potential for ergonomic improvements. The case study illustrates these applications and provides practical insights into how motion capture can transform the design and functionality of workplaces.

A R T I C L E   I N F O

Keywords:
Ergonomics;
Ergonomic risks;
Biomechanical research;
Motion capture;
Xsens suit;
Industry 4.0;
Workplace analysis;
Virtual reality

**Corresponding author:*
natasa.vujica@um.si
(Vujica Herzog, N.)

Article history:
Received 20 August 2024
Revised 27 September 2024
Accepted 29 September 2024

1. Introduction

The ergonomic design of the workplace, taking into account all the characteristics of the worker, is still a challenge for experienced and even more so for untrained ergonomists. A suitable approach should consider a system of various elements such as space, equipment, tools and devices as well as environmental influences such as noise, lighting, temperature, humidity and air velocity. Since the efficient placement of workplace elements and equipment influences productivity and employee satisfaction, our approach to workplace design is of great importance. Another important aspect that should be considered when designing the workplace is employee movements and their evaluation. Modern approaches that use motion capture systems are a major advance in the evaluation of workers' movements.

Motion capture technology is used today in industry and various other working environments. It is a technology first used in culture (movies, games and animations), but later also in other professions, in various fields of industry, medicine, sports and beyond. Several review articles have been published in recent years, indicating the topicality of the subject [1, 2]. Fig. 1 shows the results of the review by Rybnikár *et al*. [1] among the articles published in 2010-2022 with the keywords: ergonomics, motion capture, Industry 4.0, manufacturing, human factors, occupational health, safety, ergonomic assessment and work-related musculoskeletal disorders. According to Salisu *et al*., tracking the movements of the human body is currently one of the most expanding areas of research [2].

The ongoing trend of Industry 4.0 (I4.0), characterized by "smart" technologies like sensors, communication systems, simulation, and data-driven modeling, enables timely, accessible, and secure information flow, e.g. [3-8]. This trend is driving companies to gradually automate traditional manufacturing processes and update existing monitoring systems and ergonomic practices [9]. In response, concepts such as Ergonomics 4.0 and intelligent ergonomic processes have been developed to prevent risks and promote physically healthy workplaces [10, 11]. The principles of Industry 4.0 are now being integrated with the emerging Industry 5.0 paradigm to adopt a more human-centered approach to industrial work system design. According to the European Commission's 2022 guidance, Industry 5.0 enhances Industry 4.0 by focusing on research and innovation that support the transition to a sustainable, human-centered, and resilient industry.

Workers remain a vital part of production systems, performing the majority of tasks. They bring diverse skills and knowledge and vary in how they approach tasks, in terms of speed, motivation, and diligence. This diversity presents a significant challenge for companies, especially those with high employee turnover and labor-intensive processes involving substantial physical demands.

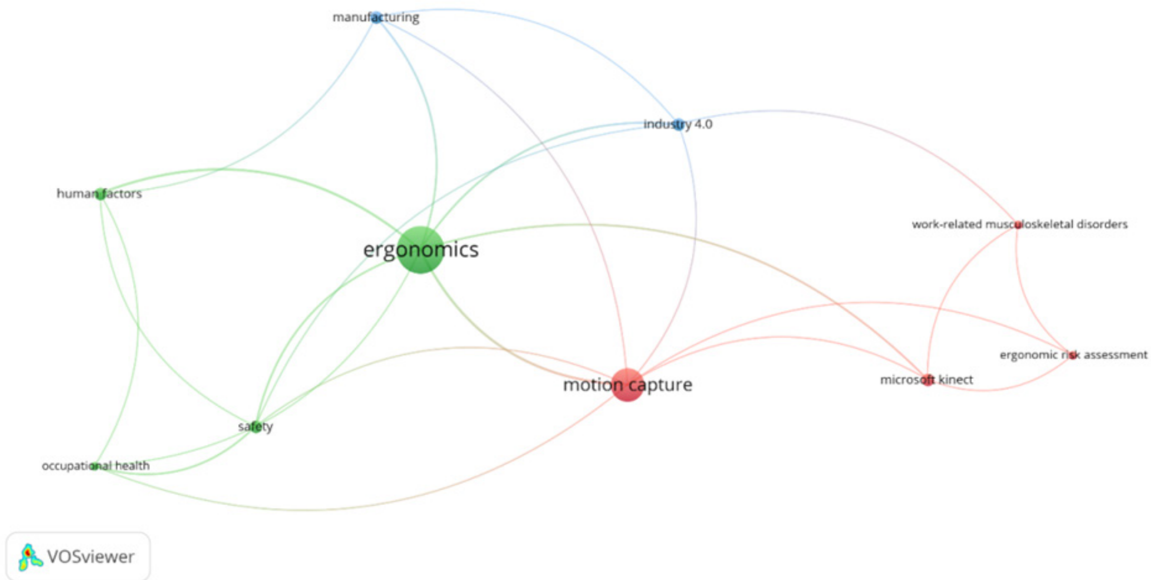

Fig. 1 Occurance of motion capture systems and ergonomics in scientific publications [1]

2. Literature review

2.1 Motion capture systems

A motion capture system is a technology that can be used to track and record the movement of individuals and objects in real time. It can be very useful for the ergonomic assessment of workplaces as it can speed up the assessment process and it is believed that the data can be analyzed more accurately than manually by an ergonomist. In the past, various approaches using different technologies have been developed to transfer the movements of workers to software that enables ergonomic analysis.

The first motion capture systems were developed in the 1960s and 1970s for military and aerospace applications. These systems used mechanical sensors and digitizers to capture the movements of pilots and astronauts. In the 1980s, the first optical motion capture systems with cameras and reflective markers were developed to track the movements of actors and performers. At the same time, pioneers in the field of biomechanics began to study the movement of humans and animals, and this knowledge was later shared. The first motion capture system that resembled modern systems was developed in the 1970s by a group of researchers at the University of Pennsylvania. This early system used reflective markers attached to the body of the person being captured, which were tracked by a series of cameras positioned around the person. The data captured by the cameras was then processed by a computer to create an animated representation of the person's movements.

An example of this group of technologies is the Vicon Motion Capture System, developed in Oxford, UK in 1979 and launched in 1984 by Oxford Medical Systems (later Oxford Dynamics) [12]. The Vicon system uses high-quality cameras and markers to track motion and is primarily used for professional motion capture applications in areas such as sports, animation and robotics. It is known for its high accuracy in motion tracking.

Kinect is a motion detection input device developed by Microsoft for its Xbox gaming console [12]. It was launched in 2010 and quickly gained popularity due to its ability to track human movement without the need for controllers or other input devices. The Kinect sensor uses a combination of cameras and depth sensors to track the movements of a person in front of it. It can detect the position and movement of individual body parts and also recognize facial expressions and voice commands. Originally developed for gaming, the Kinect is now used in a variety of other applications, such as education, healthcare and research. Its ability to track human movement in real time has made it a valuable tool for studying biomechanics, assessing progress in physiotherapy and creating interactive exhibitions. Despite its popularity, Kinect is no longer being actively developed. However, its influence on the motion capture industry and its innovative use of depth sensor technology has helped pave the way for other motion capture systems.

In the 1990s, magnetic motion capture systems were developed. These systems used magnetic fields and sensors to track movements and later, in the early 2000s, the first generation of inertial motion capture systems were developed using accelerometers and gyroscopes.

The Mocup system from Synertial [13] has been commercially available since 2004. It was developed to accurately capture and record the movement of the body of a person wearing a full body suit. It uses wireless sensors (15 on the body and 7 on each hand) attached to various parts of the body, including hands, feet, head and torso. These sensors are small, lightweight and unobtrusive, allowing a natural range of motion without interfering with the performer's movements. The sensors use an inertial measurement unit (IMU) to measure the acceleration, angular velocity and magnetic field of the body part (to improve the estimation of segment orientation) to which they are attached. This data is transmitted wirelessly to a computer where it is processed and used to create a real-time representation of the performer's movements.

Unity is a cross-platform game engine developed by Unity Technologies, first released in June 2005 [14]. Since its launch, the engine has been continuously expanded to support a wide range of platforms, including desktop, mobile, console, and virtual reality. Unity is used to create both three-dimensional (3D) and two-dimensional (2D) games, as well as interactive simulations and various other experiences. Beyond gaming, Unity has been adopted in industries such as film, automotive, architecture, engineering, construction, and even by the United States Armed Forces. Originally launched for Mac OS X, it later extended support to Microsoft Windows and web browsers.

In 2007, another interesting solution was launched, initially called Moven and then renamed Xsen's MVN in 2009 [15]. The company was founded in 2000 by two graduates of the College of Twente. The Xsens motion sensing technology, also known as motion tracking or inertial measurement units (IMUs), uses small, lightweight and highly accurate sensors that are attached to the body or objects to capture and record motion data [14]. The Xsens sensors contain accelerometers, gyroscopes and magnetometers that work together to provide highly accurate and reliable measurements of movement. The data from the sensors is processed by sophisticated algorithms to calculate the exact position, orientation and movement of the body or object in real time. This allows users to capture and analyze motion data with high precision and accuracy. This enables them to make informed decisions and create realistic and engaging digital content.

Noraxon has introduced an innovative IMU-based motion capture system that provides a versatile solution for measuring and analyzing human motion [16]. Like Xsens, it uses a series of small, lightweight IMUs attached to the body to capture joint angles, orientation and linear acceleration. Noraxon's system is characterized by its portability, which allows it to be used both in laboratory environments and in the real world. The data processed by advanced algorithms is visualized in real time via graphs and a skeletal avatar, providing immediate feedback for on-site adjustments. This makes the device an invaluable tool for researchers, clinicians and sports professionals who need accurate movement data in different environments.

The VR ErgoLog system is another type of motion capture system designed to analyze and improve human movement in virtual reality (VR) environments [17]. It is often used in sports training and rehabilitation. The system uses motion capture sensors attached to the user's body, a VR headset that immerses the user in a virtual environment, and combined with heart rate monitoring. The user can then perform various exercises or movements and the system tracks their movements in real time. The data collected by the system is analyzed by software that provides the user with feedback on their performance. This feedback can include information on posture, balance and alignment, as well as suggestions for improvement. The VR ErgoLog system is designed to be highly customizable and can adapt the level of difficulty and type of exercises to the user's specific needs. It can also be used for remote training and analysis, allowing trainers or therapists to monitor the user's progress remotely.

The HTC Vive is a virtual reality (VR) headset developed by HTC and Valve Corporation [18]. It was launched in 2016 and is known for its high-quality VR experiences. It offers room-based tracking that allows the user to move freely in a physical space while interacting with a virtual environment. The system includes a headset, two handheld controllers and two base states that enable 360-degree motion tracking. Unity and Unreal Engine are popular game engines that support the HTC Vive and allow developers to create VR experiences and integrate motion capture data. The motion capture capabilities of the HTC Vive, provided by the base stations and controllers, are highly accurate and offer low latency. This makes it suitable for various applications beyond gaming, such as training simulations and virtual prototyping.

Table 1 Motion capture systems and ergonomics

Motion capture systems	Used technology	Quality	Calibration process	Costs	Software used to process data	Ergonomics assessment
Vicon Motion capture system	Uses high-quality cameras and markers to track motion	High	Complex setup and calibration process with multiple cameras and markers	Very expensive	✓	✓
Kinect	A hardware device that uses depth-sensing cameras and microphones to track user movements and voice commands.	Medium	Relatively simple calibration and setup process	Expensive	✓	✓
Mocup system by Synertial	Based on inertial measurement units (IMUs)	High	Not particularly complex calibration process	Expensive	✓	✓
Unity	A software platform that provides developers with tools to create and deploy interactive content		Does not have a specific calibration process	Free	✓	

Table 1 (Continuation)

Xsens	Uses small motion sensors (IMU) attached to the body which communicate with a central hub to capture and analyze motion data	High	Simple calibration process	Very expensive	✓	✓
Noraxon	Uses small motion sensors (IMU) attached to the body which communicate with a central hub to capture and analyze motion data	High	Simple calibration process	Very expensive	✓	✓
VR – ErgoLog System	An inertial motion capture system integrated with immersive reality and combined with a heart rate monitoring	High	Not particularly complex calibration process	NA	✓	✓
Leap motion	Combination of optical and infrared sensors to track hand and finger movements	High	Some initial setup and calibration is needed	Cheap	✓	-
HTC Vive	Combination of advanced display technology, positional tracking, and wireless controllers to create VR experience	High	Simple calibration process	Not very expensive	✓	-

2.2 Motion capture systems in different working environments

Motion capture technology has a wide range of potential applications in different working environments, and its versatility makes it a valuable tool for improving efficiency, safety and productivity [19, 20]. The literature review by Rybnikár [1] shows the percentage of use in different sectors as follows:

- Manufacturing, 37 %,
- Logistics 23 %,
- Healthcare 17 %,
- Sports 10 %,
- Construction 7 %,
- Entertainment 7 %.

In healthcare, motion capture systems can be used to analyze patients' movements and gait to identify potential problems with balance, stability or other motor skills [21]. This information can be used to develop tailored rehabilitation programs.

It is also widely used in sports to analyze athletes' movements and improve their performance [22, 23]. It can help prevent injuries by identifying potential weak points or imbalances.

In education and training, interactive simulations can be created for training and educational purposes, e.g. for surgical training or virtual reality training for hazardous environments.

The use of motion capture systems and simulations is also important in manufacturing and on assembly lines [13, 24, 25]. It can be used to track the movements of workers on a factory floor, which can increase efficiency and reduce the risk of accidents. It can also be used to create virtual training simulations for workers to practice complex procedures in a safe and controlled environment.

Recently, it has also been used extensively when working with robots and collaborative robots [26]. Motion capture systems can be used to program and control robots so that they can mimic human movements and interact seamlessly with their environment.

2.3 Ergonomic workplace design

An effective ergonomic workplace design can lead to reduced lead and cycle times, increased productivity, lower production costs, improved return on investment, enhanced product quality and flexibility, fewer human and system errors, reduced idle time during work hours, and lower injury-related expenses. There are several ergonomic methods for evaluating the posture of workers at the workplace: Ovako Working Posture Assessment System (OWAS), Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (REBA), National Institute of Occupational Safety and Health (NIOSH), Occupational Repetitive Actions (OCRA), – Evaluacion del Riesgo Individual (ERIN), Potential Ergonomics Issue List (PEIL), Strain Index (SI) and many others [27-32].

Some methods focus on evaluating strain on specific body parts, while others offer a more comprehensive assessment. Certain approaches are tailored to different types of tasks, such as repetitive versus non-repetitive tasks, and some are designed to evaluate static loads, which in-volve maintaining the same posture for extended periods. Special attention should also be given to tasks involving manual handling. For example, an integrated approach for determining working times has been developed for assembly lines using the classical Methods Time Measurement (MTM) approach and the EAWS method for ergonomics [33]. In addition to manual assessment tools, which are time-consuming, there are also several computerized tools that reduce assessment time and usually offer several methods for body assessment (e.g. Jack, Process Simmulate, Ergomas).

2.4 Future ergonomic challanges

Aging of the population

Demographic data shows an aging world population with an increasing dominance of older workers in the labor market. Rising life expectancy and falling birth rates are leading to slower population growth and a higher proportion of older people. Although the changes associated with aging are normal, they affect the physiological and psychological functioning of individuals and impact on their ability to work and quality of life. According to Cammen et al [34], aging is a multidimensional process of change in the physical, mental and social domains that leads to functional decline.

Increased life expectancy has substantial socio-economic implications for both companies and society. As people continue to work later in life and this demographic grows, addressing workplace conditions and ensuring effective management with a focus on health and safety has become a top priority [35].

Ergonomics is fundamentally concerned with the design of the workplace according to the needs and abilities of workers. In this context, an ergonomic approach considers adequate lighting, avoiding excessive heat, taking adequate breaks and redesigning unnecessarily complex tasks. From an ergonomic perspective, maintaining age-related functionality is a priority issue for the quality of life of older people [36].

In addition, motion capture technology can be used to develop customized prostheses or assistive devices that mimic natural human movement patterns and enable older individuals to maintain their independence and quality of life. Overall, motion capture technology can play a valuable role in promoting healthy aging by helping to identify potential problems early and develop personalized interventions to address them.

Workers with disabilities

Approximately 23.5% of workers in the EU-27 region suffer from some form of chronic illness, while 19% experience long-term illnesses [37]. The highest rates of disability are found among individuals over the age of 55, with no significant difference between men and women [38]. The most commonly reported disabilities are related to back and neck issues, followed by heart conditions, high blood pressure, and problems affecting the legs and feet. Half of the disabilities were acquired outside of work, 17% were congenital, and 18% were the result of work-related injuries or conditions [38]. The severity of a disability also impacts employment, as individuals with severe disabilities are more likely to be unemployed [39].

Sex and gender in ergonomics

To explore this emerging research area, the IEA established the Technical Committee (TC) on Gender and Work in 2006 [40]. Since then, numerous committees have been formed across vario-us countries to examine the connections between sex, gender, health, and work in different oc-cupational sectors. Collectively, these efforts highlight ergonomics as both a theoretical and prac-tical discipline, developing innovative methods to incorporate sex and gender analysis into policy development and evaluation. Gender considerations were presented for various evaluation methods, working conditions and impact/process benefits in ergonomic interventions.

3. Materials and methods

To gain deeper insights into the topic, a case study was conducted using Xsens sensors [15] to capture human movements, which were later analyzed from an ergonomic perspective using the Process Simulate software (Siemens PLM Software). The sensors were directly attached to the body, allowing measurements to be taken in a natural environment and in real time. The ergonomic assessment of the worker's postures and movements was performed using the OWAS and RULA method [27, 28].

3.1 Process Simulate

Process Simulate is one of the many computer programs for the simulation and optimization of manufacturing processes developed by Siemens Digital Industries. It is a comprehensive platform for the development, simulation, validation and thus optimization of production in manufacturing environments. In our research, we used it to create a digital model of the workplace under investigation and to carry out ergonomic validation. The program enables the input of human movements and positions recorded with the Xsens suit. The Task Simulation Builder (TSB) in Process Simulate can also be used to create/edit the simulation of human movements. Minor corrections were made to the movements captured with the Xsens suit via the TSB interface.

3.2 Xsens suit

Founded in 2000 and now part of Movella, Xsens specializes in 3D motion sensing technology, offering wearable sensors and inertial devices that leverage miniature MEMS technology. The company provides innovative and precise solutions for real-time tracking and analysis of human and object movements. Its sensors, which include accelerometers, gyroscopes, and magnetometers, are placed on different body parts to measure acceleration, angular velocity, and spatial orientation. Advanced algorithms process this data to accurately reconstruct 3D movements.

In our research, we used the Xsens MVN Awinda system, which includes 17 wireless motion sensors (Fig. 2). These sensors are securely attached to a special Lycra suit and straps to ensure proper fixation. Fig. 2 shows the body parts and the position of sensors.

Fig. 2 Xsens MVN Awinda system for body movement data gathering and Xsens suit with sensors

The biomechanical model used in this system consists of 23 segments: pelvis, vertebrae (L5*, L3*, T12*, T8), neck*, head, shoulders, upper arms, lower arms, hands, thighs, lower legs, feet, and toes*. Segments marked with * do not have dedicated sensors; their movement is estimated by integrating data from the adjacent segments and the biomechanical model. By combining sensor data and correcting for errors—since the sensors are not rigidly connected to the body segments—a precise and drift-free estimate of the relative position and orientation of each segment is achieved.

To ensure accuracy, sensor calibration is necessary to account for factors that may affect measurement precision. This sensor-to-segment calibration typically involves standing in a known pose (e.g., N or T pose) and estimating sensor orientation by processing the sensor readings (Fig. 3). Gyroscopes detect short-term orientation changes, while accelerometers and magnetometers maintain long-term stability.

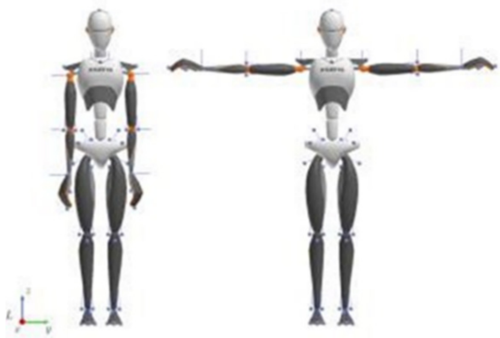

Fig. 3 Xsens MVN avatar in N-pose (left) and T-pose (right)

3.3 OWAS and RULA method

The OWAS method [27] was used for the ergonomic assessment of human movements, evaluating 28 postures. These include the back (four positions), upper limbs (four), hands (three), lower limbs (nine), head and neck (five), and the load or force applied (three). Each posture is classified into one of the following risk categories:

- Green: No changes needed,
- Yellow: Changes needed in the near future,
- Orange: Immediate changes required,
- Red: Requires intensive observation.

The Process simulate software enables various ergonomic analyses; we therefore also carried out an analysis using the RULA method to compare the results. The RULA method (Rapid Upper Limb Assessment) is an ergonomic tool for assessing the risk of musculoskeletal injuries in the workplace, particularly in relation to the upper limbs [28]. The aim is to observe the positions of certain body segments individually in order to determine the degree of deviation from neutral posture. The greater the deviation, the higher the score assigned to the respective body part.

3.4 Research environment and measuring procedures

The research was conducted in the laboratory of the Faculty of Mechanical Engineering at the University of Maribor, which is fully equipped to transfer human movements into a virtual environment. A specialized Xsens training suit, fitted with 17 sensors, was used to capture human movements, positions, and postures. During the process, a receiver collects the data from the suit and records it on a PC. The data is processed using the Xsens MVN software to generate a simulation. Simultaneously, the human movements were recorded in real time via video, which was later used to recreate the movements using Task Simulation Builder (TSB).

For the case study demonstration with the Xsens suit, we designed a simple polygon created with Process Simulate software (Fig. 4) that contained the following tasks:

- Walk to the table,
- Get a small box with both hands,
- Bring the box to the locker,
- Put the box on the locker,
- Walk to the chair,
- Get the chair,
- Place the chair to the table.

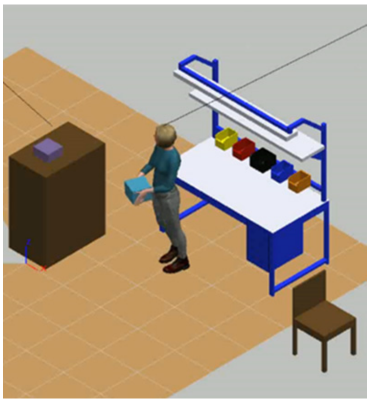


Fig. 4 Workplace created with Process Simulate software and Xsens suit with 17 sensors

5. Results and discussion

The movements of workers simulated using the Process Simulate software package were assessed with the OWAS ergonomic method first. We examined these movements with two human models representing different ages: 25 and 60 years old. Fig. 5 shows some of the positions of the human model that were performed during the simulation for the selected postures of a 25-year-old woman on the left and a 60-year-old woman on the right.

Figs. 6 and 7 display the cumulative OWAS analysis results for both age groups, with slight differences noted in the movements highlighted in orange and red.

Overall, the analysis results are similar for most simulated movements. However, a significant difference was observed in one specific posture—when turning to walk to another point (see Figs. 5, 6, and 7). For the 25-year-old model, the actions was marked in orange, indicating a moderately high risk and recommending prompt changes. Conversely, for the 60-year-old model, the same actions was marked in red, signifying a very high risk and recommending immediate changes. For further details on the research, please refer to the chapter published by DAAAM International Scientific Book [41].

During the research, we also compared ergonomic analyses performed manually with TSB interface with those based on data from the Xsens suit. The postures selected and designed by the TSB programme in Process Simulate are more ergonomic as they are selected by the programme itself, resulting in lower risk scores. An example of this is the posture in which the woman lifts the chair and places it at the desk (Fig. 8). In the simulation carried out with the suit, this posture is regarded as unergonomic and categorised as risk level 4. However, in the simulation performed by the programme, this posture represents a lower risk and is classified as level 2. This is because the simulation performed by the programme ensures a correct grip posture of the chair, in contrast to the other simulation.

Table 2 shows some of the results of the RULA method for the most important postures. As we can see, there is one posture that refers to Jill bending over to push the chair. According to RULA, this posture should be analysed and changed immediately.

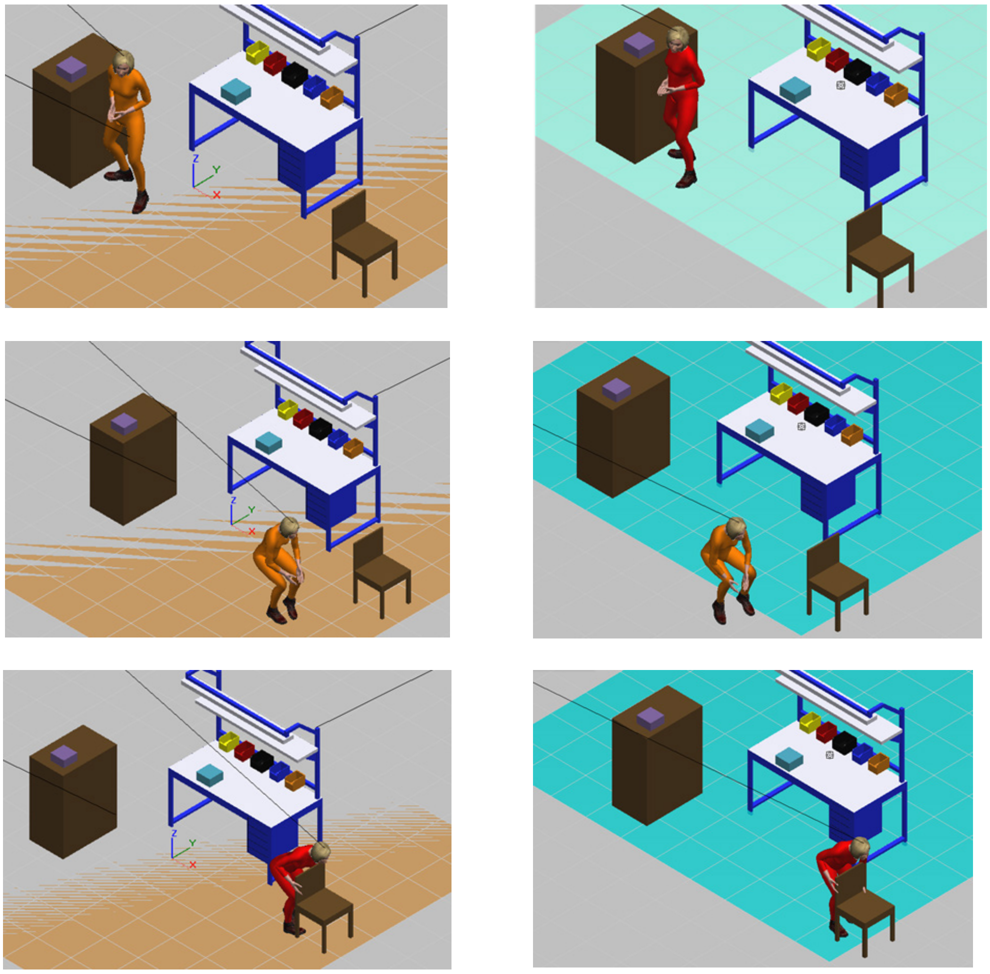

Fig. 5 Working environment with 25 and 60 year-old person

Time (Sec)	Operation	Object Weight (kg)	Action Category	Code Posture Combination					
				Back	Arms	Legs	Load	-	Head
0	Frame 4	0	1	1	1	2	1	-	1
0.2		0	2	1	1	4	1	-	1
8.3	Frame 88	0	3	2	1	4	1	-	1
8.7	Frame 94	0	2	1	1	4	1	-	1
16.25	Frame 175	0	3	2	1	4	1	-	1
16.9	Frame 181	0	2	1	1	4	1	-	1
19.2	Frame 205	0	3	2	1	4	1	-	1
22.45	Frame 241	0	4	4	1	4	1	-	1
23.1	Frame 247	0	3	2	1	4	1	-	1
23.8	Frame 253	0	2	1	1	4	1	-	1
24.2	Frame 259	0	3	2	1	4	1	-	1
24.3		0	2	1	1	4	1	-	1
24.5	Frame 262	0	3	2	1	4	1	-	1
25.3	Frame 271	0	4	4	1	4	1	-	1
26.5	Frame 283	0	3	2	1	4	1	-	1
27.2	Frame 289	0	2	1	1	4	1	-	1
27.5	Frame 292	0	3	2	1	4	1	-	1
27.6	Frame 295	0	2	1	1	4	1	-	1
28	Frame 298	0	3	2	1	4	1	-	1
29	Frame 310	0	2	1	1	4	1	-	1
29.1		0	3	2	1	4	1	-	1
29.3	Frame 313	0	2	1	1	4	1	-	1
30.9	Frame 331	0	3	2	1	4	1	-	1
32.2	Frame 343	0	3	2	1	4	1	-	4
33.5	Frame 358	0	3	2	1	4	1	-	1
36.8	Frame 394	0	2	1	1	4	1	-	1

Fig. 6 OWAS results: 25-year-old model

Time (Sec)	Operation	Object Weight (kg)	Action Category	Code Posture Combination					
				Back	Arms	Legs	Load	-	Head
22.2	Frame 406	0	2	1	1	4	1	-	1
22.25		0	3	3	1	4	1	-	1
22.5	Frame 412	0	2	1	1	4	1	-	1
22.59	Frame 415	0	3	2	1	4	1	-	1
23.38	Frame 430	0	3	2	1	4	1	-	4
23.5		0	4	4	1	4	1	-	4
23.6	Frame 433	0	3	2	1	4	1	-	4
23.85	Frame 436	0	4	4	1	4	1	-	4
24.15	Frame 442	0	3	2	1	4	1	-	4
24.34	Frame 448	0	3	2	1	4	1	-	1
24.93	Frame 460	0	2	1	1	4	1	-	1
29.05	Frame 535	0	3	2	1	4	1	-	1
29.55	Frame 544	0	3	2	1	4	1	-	4
31.65	Frame 583	0	3	2	1	4	1	-	1
34.55	Frame 637	0	2	1	1	4	1	-	1

Fig. 7 OWAS results: 60-year-old model

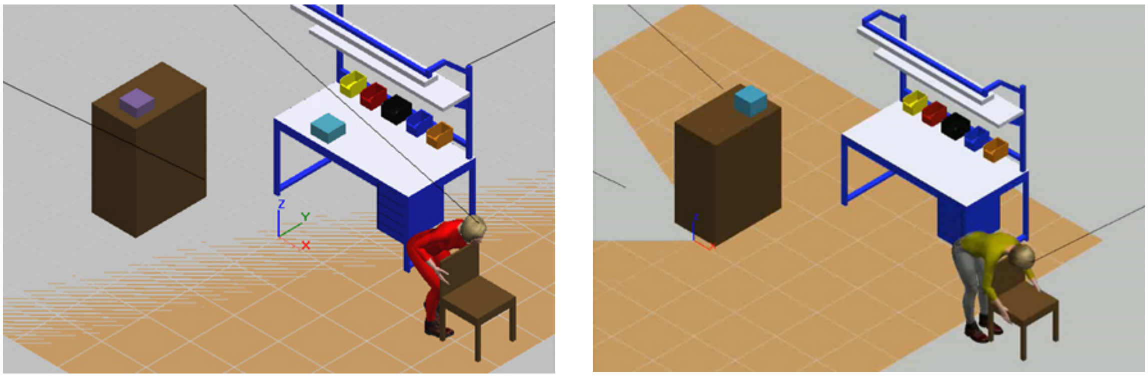

Fig. 8 Taking chair from Recording on the left and Taking chair from Simulation on the righ

Table 2 Compilation of results of the RULA method for the most relevant postures

Position	25 year-old person	60 year-old person
Put_chair_Jill_1_Release	2	2
Go_to_target_Jill_Arrise_From_Bend	4	4
Put_box_Jill_Release	3	3
Put_part1_Jill_Bend_and_Reach	7	7
Go_to_target_Jill_Arrise_From_Bend	6	7
Go_to_target_Jill_Walk	4	4
Put_chair_Jill_Bend_and_Reach	7	7
Put_chair_Jill_Reach	6	6

6. Conclusion

The study of workplace ergonomics is essential for promoting worker health, well-being, and productivity. Ergonomic principles aim to tailor the work environment to individual needs, optimizing the interaction between workers, tasks, and their surroundings. This approach helps prevent injuries, reduce fatigue and stress, and improve performance and job satisfaction, benefiting both employees and companies. Recent advancements in motion capture systems have contributed significantly to ergonomic workplace design. These systems are highly valuable for virtual reality applications, detailed biomechanical analyses, and exploring ways to integrate motion capture into human-computer interactions. Additionally, they facilitate access for individuals with disabilities, promoting more inclusive participation across various environments.

The mailn contribution of the paper is an overview of motion capture technology and the possible integration with ergonomic assessment methods. It presents various possibilities and discusses future challenges in ergonomics.

A case study is included to demonstrate new technologies, such as the Xsens suit and Process Simulate software, in ergonomic workplace design, with a focus on older workers. This study has three limitations. First, while the findings offer valuable insights through a case study, they should be viewed as preliminary. The primary value of this research lies in its role as a pilot study. Since it is based on a single case, the results cannot be generalized. Future studies need to include a larger sample to validate the results in a broader population. Second, there may be discrepancies between the OWAS measurements obtained using the Xsens motion capture system and the data obtained by direct observation. Although we have made considerable efforts to minimize these differences by performing a frame-by-frame analysis, discrepancies may still occur. Finally, although OWAS and RULA were used for ergonomic assessment in this study, there are numerous other methods to assess physical strain. It is important to investigate whether these alternative methods can also be used reliably with motion capture data. Furthermore, given the real-time analysis capability offered by systems such as Xsens, this study points to the potential need to develop new methods of ergonomic assessment that go beyond traditional approaches and are tailored to take full advantage of modern motion capture technology.

In conclusion, motion capture technology offers significant advantages for ergonomic workplace design, providing efficient and accurate solutions. The conducted research has demonstrated great potential; however, future studies will need to be expanded, include a larger number of repetitions to verify the reliability of the equipment.

Acknowledgement

The authors thank the reviewers and the editor for their comments. This work was supported by the Slovenian Research Agency under Grant P2-0190. We also acknowledge the use of research equipment system for development and testing cognitive production approaches in Industry 4.0, procured within the project RIUM, which was co-financed by the Republic of Slovenia, the Ministry of Education, Sci-ence and Sport and the European Union from the European Regional Development Fund.

References

[1] Rybnikár, F., Kačerová, I., Hořejší, P., Šimon M. (2023). Ergonomics evaluation using motion capture technology - Literature review, *Applied Sciences,* Vol. 13, No. 1, Article No. 162, doi: 10.3390/app13010162.

[2] Salisu, S., Ruhaiyem, N.I.R., Eisa, T.A.E., Nasser, M., Saeed, F., Younis, H.A. (2023). Motion capture technologies for ergonomics: A systematic literature review, *Diagnostics,* Vol. 13, Article No. 2593, doi: 10.3390/diagnostics13152593.

[3] Rosin, F., Forget, P., Lamouri, S., Pellerin, R. (2021). Impact of Industry 4.0 on decision-making in an operational context, *Advances in Production Engineering & Management*, Vol. 16, No. 4, 500-514, doi: 10.14743/apem2021.4.416.

[4] Bun, P., Grajewski, D., Gorski, F. (2021). Using augmented reality devices for remote support in manufacturing: A case study and analysis, *Advances in Production Engineering & Management*, Vol. 16, No. 4, 418-430, doi: 10.14743/apem2021.4.410.

[5] Wawak, S., Sutoova, A., Vykydal, D., Halfarova, P. (2023). Factors affecting Quality 4.0 implementation in Czech, Slovak and Polish organizations: Preliminary research, *Advances in Production Engineering & Management,* Vol. 18, No. 3, 345-356, doi: 10.14743/apem2023.3.477.

[6] Stefanovska, E., Pepelnjak, T. (2022). Development of a flexible tooling system for sheet metal bending, *Advances in Production Engineering & Management,* Vol. 17, No. 3, 311-325, doi: 10.14743/apem2022.3.438.

[7] Lasota, A.M. (2020). A new approach to ergonomic physical risk evaluation in multi-purpose workplaces, *Tehnički Vjesnik – Technical Gazette,* Vol. 27, No. 2, 467-474, doi: 10.17559/TV-20180312131319.

[8] Lyu, J., Peng, Q., Chen, M. (2022). Influence of body mass index on comfort and parametric optimization design of seat, *Tehnički Vjesnik – Technical Gazette,* Vol. 29, No. 4, 1262-1269, doi: 10.17559/TV-20210306023605.

[9] Diego-Mas, J.-A., Poveda-Bautista, R., Garzon-Leal, D.-C. (2015). Influences on the use of observational methods by practitioners when identifying risk factors in physical work, *Ergonomics,* Vol. 58, No. 10, 1660-1670, doi: 10.1080/00140139.2015.1023851.

[10] Kadir, B.A., Broberg, O., da Conceição,C.S. (2019). Current research and future perspectives on human factors and ergonomics in Industry 4.0, *Computers & Industrial Engineering,* Vol. 137, Article No. 106004, doi: 10.1016/j.cie.2019.106004.

[11] Lanzotti, A., Vanacore, A., Tarallo, A., Nathan-Roberts, D., Coccorese, D., Minopoli, V., Carbone, F., d'Angelo, R., Grasso, C., Di Gironimo, G., Papa, S. (2019). Interactive tools for safety 4.0: Virtual ergonomics and serious games in real working contexts, *Ergonomics,* Vol. 63, No. 3, 324-333, doi: 10.1080/00140139.2019.1683603.

[12] Dutta, T. (2012). Evaluation of the Kinect sensor for 3-D kinematic measurement in the workplace, *Applied Ergonomics*, Vol. 43, No. 4, 645-649, doi: 10.1016/j.apergo.2011.09.011.

[13] Simonetto, M., Arena, S., Peron, M. (2022). A methodological framework to integrate motion capture system and virtual reality for assembly system 4.0 workplace design, *Safety Science,* Vol. 146, Article No. 105561, doi: 10.1016/j.ssci.2021.105561.

[14] Peruzzini, M., Grandi, F., Cavallaro, S., Pellicciari, M. (2021). Using virtual manufacturing to design human-centric factories: An industrial case, *The International Journal of Advanced Manufacturing Technology,* Vol. 115, 873-887, doi: 10.1007/s00170-020-06229-2.

[15] Roetenberg, D., Luinge, H., Slycke, P. (2013). *Xsens MVN: Full 6DOF human motion tracking using miniature inertial sensors,* Xsens technologies – Version April 3, from *https://www.researchgate.net/publication/239920367_Xsens_MVN_Full_6DOF_human_motion_tracking_using_miniature_inertial_sensors*, accessed August 13, 2024.

[16] Cottam, D.S., Campbell, A.C., Davey, M.P.C., Kent, P., Elliott, B.C., Alderson, J.A. (2022). Measurement of uni-planar and sport specific trunk motion using magneto-inertial measurement units: The concurrent validity of Noraxon and Xsens systems relative to a retro-reflective system, *Gait & Posture,* Vol. 92, 129-134, doi: 10.1016/j.gaitpost.2021.11.012.

[17] Battini, D., Calzavara, M., Persona, A., Sgarbossa, F., Visentin, V., Zennaro, I. (2018). Integrating mocap system and immersive reality for efficient human-centred workstation design, *IFAC – PapersOnLine,* Vol. 51, No. 11, 188-193, doi: 10.1016/j.ifacol.2018.08.256.

[18] Khan, S., Park, J.-W., Ham, S. (2023). Noncontact structural displacement measurements using a low-cost motion tracking system, *IEEE Sensors Journal,* Vol. 23, No. 11,11695-11703, doi: 10.1109/JSEN.2023.3267450.

[19] Kačerová, I., Kubr, J., Hořejší, P., Kleinová, J. (2022). Ergonomic design of a workplace using virtual reality and a motion capture suit, *Applied Science,* Vol. 12, No. 4, Article No. 2150, doi: 10.3390/app12042150.

[20] Dolgui, A., Sgarbossa, F., Simonetto, M. (2021). Design and management of assembly systems 4.0: Systematic literature review and research agenda, *International Journal of Production Research*, Vol. 60, No. 1, 184-210, doi: 10.1080/00207543.2021.1990433.

[21] Rudigkeit, N., Gebhard, M. (2020). AMiCUS 2.0 – System presentation and demonstration of adaptability to personal needs by the example of an individual with progressed multiple sclerosis, *Sensors,* Vol. 20, No. 4, Article No. 1194, doi: 10.3390/s20041194.

[22] Van der Kruk, E., Reijne, M.M. (2018). Accuracy of human motion capture systems for sport applications; State-of-the-art review, *European Journal of Sport Science,* Vol. 18, No. 6, 806-819, doi: 10.1080/17461391.2018.1463397.

[23] Ghattas, J., Jarvis, D.N. (2021). Validity of inertial measurement units for tracking human motion: A systematic review, *Sports Biomechanics,* 1-14, doi: 10.1080/14763141.2021.1990383.

[24] Bortolini, M., Faccio, M., Gamberi, M., Pilati, F. (2020). Motion Analysis System (MAS) for production and ergonomics assessment in the manufacturing processes, *Computers & Industrial Engineering*, Vol. 139, Article No. 105485, doi: 10.1016/j.cie.2018.10.046.

[25] Grznar, P., Gregor, M., Gola, A., Nielsen, I., Mozol, S., Seliga, V. (2022). Quick workplace analysis using simulation, *International Journal of Simulation Modelling,* Vol. 2,No. 3, 465-476, doi: 10.2507/IJSIMM21-3-612.

[26] Ojstersek, R., Javernik, A., Buchmeister, B. (2022). Importance of sustainable collaborative workplaces – Simulation modelling approach, *International Journal of Simulation Modelling,* Vol. 21, No. 4, 627-638, doi: 10.2507/IJSIMM21-4-623.

[27] Karhu, O., Härkönen, R., Sorvali, P., Vepsäläinen, P. (1981). Observing working postures in industry: Examples of OWAS application, *Applied Ergonomics,* Vol. 12, No. 1, 13-17, doi: 10.1016/0003-6870(81)90088-0.

[28] McAtamney, L., Corlett, E.N. (1993). RULA: A survey method for the investigation of work-related upper limb disorders, *Applied Ergonomics,* Vol. 24, No. 2, 91-99, doi: 10.1016/0003-6870(93)90080-s.

[29] Hignett, S., McAtamney, L. (2000). Rapid entire body assessment (REBA), *Applied Ergonomics,* Vol. 31, No. 2, 201-205, doi: 10.1016/s0003-6870(99)00039-3.

[30] Occhipinti, E., Colombini, D. (2002). Updating reference values and predictive models of the OCRA method in the risk assessment of work related musculoskeletal disorders of the upper limbs, *Ergonomics,* Vol. 50, No. 11, 1727-1739, doi: 10.1080/00140130701674331.

[31] Kee, D., Karwowski, W. (2007). A comparison of three observational techniques for assessing postural loads in industry, *International Journal of Occupational Safety and Ergonomics*, Vol. 13, No. 1, 3-14, doi: 10.1080/10803548.2007.11076704.

[32] Vujica Herzog, N., Buchmeister, B. (2015). The review of ergonomics analysis for body postures assessment, In: Katalinić, B. (ed.), *DAAAM International scientific book 2015,* DAAAM International, Vienna, Austria, 153-164, DAAAM International scientific book, doi: 10.2507/daaam.scibook.2015.14.

[33] Schaub, K., Caragnano, G., Britzke, B., Bruder, R. (2013). The European assembly worksheet, *Theoretical Issues in Ergonomics Science*, Vol. 14, No. 6, 616-639, doi: 10.1080/1463922X.2012.678283.

[34] van der Cammen, T.J.M., Wang, G., Albayrak, A. (2019). Where ergonomics meets geriatrics: The connection between comprehensive geriatric assessment and design for ageing, *European Geriatric Medicine*, Vol. 10, 333-335, doi: 10.1007/s41999-019-00171-7.

[35] Araújo-Vila, N., Toubes, D.R., Fraiz-Brea, J.A. (2022). The age factor in the analysis of occupational risks in the wood industry, *Healthcare,* Vol. 10, No. 7, Article No. 1355, doi: 10.3390/healthcare10071355.

[36] Pamuk, D., Faezi, S.A., Başıbüyük, G.Ö. (2022). Ergonomics and aging: A bibliometric analysis, *Work,* Vol. 72, No. 3, 853-864, doi: 10.3233/WOR-210112.

[37] Vujica-Herzog, N., Harih, G. (2019). Decision support system for designing and assigning ergonomic workplaces to workers with disabilities, *Ergonomics,* Vol. 63, No. 2, 1-13, 225-236, doi: 10.1080/00140139.2019.1686658.

[38] Dupré, D., Karjalainen, A. (2003). *Eurostat, statistics in focus: Employment of disabled people in Europe in 2002, Eurostat, Theme 3: Population and Social Conditions,* Eurostat, Luxembourg, 1-8, from *https://aei.pitt.edu/85492/1/2003.26.pdf*, accessed August 13, 2024.
[39] Greve, B. (2009). *The labour market situation of disabled people in european countries and implementation of employment policies: A summary of evidence from country reports and research studies*, Academic Network of European Disability Experts (ANED), from *https://www.academia.edu/1902383/The_labour_market_situation_of_disabled_people_in_European_countries_and_implementation_of_employment_policies_A_summary_of_evidence_from_country_reports_*, accessed August 13, 2024.
[40] Laberge, M., Caroly, S., Riel, J. Messing, K. (2020). Considering sex and gender in ergonomics: Exploring the hows and whys, *Applied Ergonomics,* Vol. 85, Article No. 103039, doi: 10.1016/j.apergo.2019.103039.
[41] Vujica Herzog, N., Kaya, Ö; Buchmeister, B. (2023). Ergonomics and ageing – Case study, In: Katalinić, B. (ed.), *DAAAM International scientific book 2023,* DAAAM International, Vienna, Austria, 17-32, doi: 10.2507/daaam.scibook.2023.02.