www.czasopisma.pan.pl PAN www.journals.pan.pl

Management and Production Engineering Review
Volume 15 • Number 1 • March 2024 • pp. 182–192
DOI: 10.24425/mper.2024.149999

Digital Human Modeling in Improving the Ergonomics of Industrial Workplace – a Methodological framework

Andrzej Marek LASOTA[1], Krzysztof HANKIEWICZ[2]

[1] *Institute of Mechanical Engineering, University of Zielona Gora, Poland*
[2] *Faculty of Engineering Management, Poznan University of Technology, Poland*

Received: 18 December 2023
Accepted: 14 February 2024

Abstract
In the era of Industry 4.0, digital human modeling (DHM) may be the key to improving ergonomics related to manual operations in the workplace. Poor workplace ergonomics may lead to reduced work productivity and an increased risk of health problems among employees, resulting in actual losses for enterprises, e.g., sickness absence, employee turnover, and training. DHM technology can help speed up ergonomic analysis and improvement. This paper proposes a methodological framework based on DHM to improve ergonomics in the workplace. Its purpose is to provide practitioners with an easy and detailed approach to ergonomics assessment and improvement procedures. The framework developed two main stages: the workplace Research Stage and the DHM and Simulation Stage, which cover the eight detailed steps of an effective DHM-based ergonomic assessment together. A case study was used to verify and demonstrate the effectiveness of the proposed methodological framework.

Keywords
digital simulation, ergonomics, risk, methodology, production, efficiency.

Introduction

Industry constantly strives to be competitive in the market in the production of goods, taking into account quality and productivity. At the same time, it is essential to offer employees a sustainable working life (Zink, 2014). Workplace health and safety are crucial for all employees in work environments to ensure efficient work and productivity (Kar & Hedge, 2021). Ergonomic risk factors can have a negative impact on workers while performing their tasks (Lasota & Hankiewicz, 2016; Taibi et al., 2021).

Ergonomics or human factors as a scientific discipline focuses on adapting workplaces and systems to people and improving their well-being. It makes an important contribution to the design and assessment of tasks, jobs, products, work environments, and organizational systems so that they meet employees' needs, capabilities, and limitations (*IEA*, 2023). Ergonomics is also the science of adapting workplaces, machines, and devices to humans to ensure safety and optimal efficiency so as not to force employees to adapt to non-ergonomic workstations and tasks, which may hurt their health and workplace well-being (Lasota & Hankiewicz, 2017b). Therefore, machines, tools, workplaces, and work environments must be best adapted to human capabilities and limitations. It is a process of continuous improvement of the work environment (machines, equipment, workload, work pace, etc.) to adapt to the employees' physical requirements and limitations (Tytyk, 2001). Poor ergonomics and ergonomic risk factors, including the operator's posture during work, range of motions, applied force, repetition, and duration of work movements, may lead to work-related musculoskeletal disorders (WRMSDs) in operators (Bernard & Putz-Anderson, 1997; Haynes & Williams, 2008; Lasota, 2014). A low level of ergonomic quality may have a negative impact on employees and limit the development of the company. Adverse effects on employees manifest themselves in the form of WRMSDs, fatigue, pain, illness, and loss of productivity. However, in the workplace, they include absenteeism and higher costs related to higher employee turnover and the need to train newly employed people. In 2019, approximately 1.71 billion people globally suffered from musculoskeletal problems in 204 countries

Corresponding author: *Andrzej Marek Lasota – Institute of Mechanical Engineering, University of Zielona Gora, Prof. Z. Szafrana 4, 65-516, Zielona Gora, Poland, e-mail: A.Lasota@iim.uz.zgora.pl*

analyzed by Cieza et al. (Cieza et al., 2020). In 2020, musculoskeletal system diseases were the second most common cause of employee sickness absence in Poland. They accounted for 16.1% of all absences from work and resulted in 41.3 million days lost due to sick leave (Sickness absence in 2020), determining a significant financial burden. In contrast, in the European Union, the costs of all absences due to WRMSDs have been estimated at 2.1% to 3.1% of the EU gross domestic product (European Agency for Safety and Health at Work, 2010). Therefore, it is essential to use ergonomics, which can increase savings and productivity, reduce employee injuries, increase work engagement and workplace well-being (Macdonald & Oakman, 2022), and reduce absenteeism (Quiroz-Flores et al., 2023).

Ergonomic evaluation and analysis are tools for assessing risk and necessary changes as an ergonomic intervention (Lasota & Hankiewicz, 2017a). They are commonly carried out by practitioners using techniques based on observation (David, 2005; Takala et al., 2010). One of the elements of an effective ergonomic assessment is ergonomic diagnostics. Diagnostics aims to find the primary causes of irregularities that cause ergonomic risk higher than minimal (Tytyk, 2001). However, observation techniques are time-consuming, and the result may depend on the subjective judgment of the ergonomist. More advanced ergonomics tools, such as Digital Human Modeling (DHM) and simulation have been developed to support proactive ergonomics research. DHM technology allows for early and easier identification of ergonomic problems and reduces or sometimes eliminates the need for physical and real-world operator testing. The DHM technique was developed to help and support engineers in ergonomic design and assessment. It enables the visualization of a 3D model of an employee engaged in performing tasks. DHM programs usually include some functions e.g., human manikin movement, ergonomic analysis, limb reach analysis, and the ability to scale the 3D manikin based on available anthropometric data (Grobelny and Michalski, 2020). Examples of commercially available DHM software packages include Jack – Process Simulate Human (Human Centered Design and Simulation |Siemens Software), DELMIA (DELMIA, 2023), SAMMIE (SAMMIE CAD Ltd), and SANTOS (SantosHuman). Typically, DHMs include virtual environments for modeling and simulating employee postures and WRMSD risk assessment tools. Work process simulation helps end users redesign the workplace to reduce potential hazards and eliminate harmful and uncomfortable postures and movements (Grobelny & Michalski, 2020).

The current industrial revolution, called Industry 4.0, causes many challenges for manufacturing companies (Hamrol et al., 2019). Nowadays, companies are adapting to the requirements of Industry 4.0, where digitalization is a key element. However, work ergonomics is an important component. It seems that in small and medium-sized enterprises, the process of adapting to Industry 4.0 will be slower compared to leading and technologically advanced companies due to the company's capital, including its technological, organizational, and financial capabilities. Hence, there is a need to develop a methodological framework enabling the easy use of ergonomic assessments and improving the ergonomics of individual workplaces. This will allow for evolutionary adaptation to the challenges of Industry 4.0. Therefore, this study aims to develop a flexible and easy-to-use methodological framework using a digital environment to improve ergonomic indicators. It was validated by a case study covering the steps necessary to improve ergonomics at the workplace. The framework takes into account not only ergonomics but also the work process to ensure worker well-being and optimal system performance.

The methodological framework proposed in this paper is addressed to production engineers, ergonomists, and teams involved in improving production systems based on ergonomics.

Literature review

DHM technology is gaining increasing interest among researchers because it allows for obtaining realistic results both in the design process and in the assessment of ergonomic indicators in the workplace (Cao, 2011; Hussain et al., 2019; Maurya et al., 2019). DHM has been used for recognizing acceptable postures at computer workstations (Estrada & Vea, 2018), for improving the design of production cells in car manufacturing plants (Spada et al., 2017), for assessing assembly tasks in the automotive industry (Feyen et al., 2000), and for tasks related to manual material handling (Wagner et al., 2007). It is also used in aviation (Bernard et al., 2020; Sanjog et al., 2015), in surgical wards (Bartnicka, 2015), in an occupational safety and health process (Schall Jr et al., 2018), in a brewing company (Ji et al., 2023), in waste sorting tasks (Emmatty et al., 2021), and to improve the work environment for the elderly and people with disabilities (Maurya et al., 2019).

In turn, in the literature, several authors have developed methodological frameworks linking ergonomics with enterprise operations. Radin Umar et al. (2023) developed a framework that integrated ergonomics with the Lean 3M concept, including Muda (waste), Muri (overburden), and Mura (unevenness). Based on interviews with Lean practitioners, the authors discovered four elements connecting ergonomics with 3M Lean: (1) wasting energy by humans; (2) uneven distribution of human workload; (3) overloading employee capabilities; and (4) the fact that performance employee affects work performance.

Caterino et al. (2023) presented an evaluation framework for the ergonomic risk assessment of heterogeneous workers based on a digital environment. The framework is designed to perform ergonomic simulations of complex work systems, taking into account the number of workers.

Sun et al. (2018) proposed a framework for designers to integrate task-oriented ergonomics from the early design phase. In turn, Morag and Luria (2013) presented a framework for risk analysis based on participatory ergonomics.

Neumann and Village (2012) proposed a framework for integrating ergonomics into the design of a work system that can support efforts to incorporate human factors into the design process to improve the system and the cost-effective application of ergonomics.

Battini et al. (2011) proposed a framework to improve efficiency and ergonomics in the design of assembly systems. The framework is based on an engineering approach to the design of assembly systems and considers ergonomic optimization of the workplace.

Lasota and Hankiewicz (2017a) proposed a framework for the ergonomic assessment of multi-task workplaces, paying attention to the variability of tasks performed.

In some cases, the developed methodological framework refers to design; in others, it refers to assembly systems that take into account the principles of ergonomics. The framework presented in the literature review focuses on specific areas, and there is a gap that the framework proposal presented in this work seeks to fill by providing enterprises with a tool for evolutionary adaptation to the requirements of Industry 4.0.

Research methodology

The proposed new research approach is a methodological framework with sequential steps (Fig. 1). The developed framework includes two main stages: Stage 1 – research study and Stage 2 – digital human modeling and simulation. Stage 1 includes a workplace study for ergonomic improvement and data collection. Stage 2 – digital modeling of the workplace in a virtual environment, ergonomic assessment, and improvement. Generally, research based on this framework consists of eight consecutive steps (three steps – Stage 1; five steps – Stage 2). Each step requires input from the previous step and provides its output to subsequent steps.

The detailed steps of the methodological framework are presented below.

Stage 1 – Research study

Step 1: General inspection of workplaces

The first key step is to make general observations and visual inspections of workplaces. General visual observation, direct interviews, and discussions with managers and production engineers can help identify and understand workplaces. The collected information should help the evaluator understand the work environment, tasks, and activities the operator performs and help select workplaces for ergonomic assessment and possible improvement.

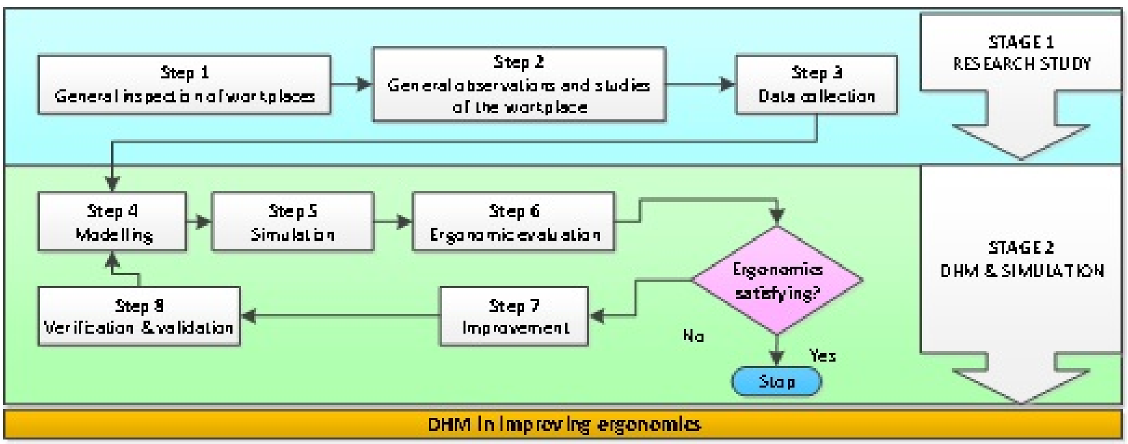

Fig. 1. Flowchart of the methodological framework

Step 2: General observations and studies of the workplace

General observations and analysis of a selected workplace allow for deepening knowledge about the position, equipment, and task being performed. Information collected from observations of the employee during his or her daily work in the actual work environment, as well as from discussions and face-to-face interviews, should be used to identify the tasks performed at the workplace selected for assessment. This can help identify any problems or difficulties in performing tasks, including prioritization and sequencing of assessments, data collection methods, and assessment strategy.

Step 3: Data collection

Data regarding the workplace, equipment, operations performed, movements, applied forces, etc. are collected to reproduce the workplace and the task performed in the virtual environment.

Stage 2 – DHM and simulation

Step 4: Modeling

Workplace modeling in a virtual environment includes machines, devices, equipment, and their arrangements. A mannequin model is selected in this step.

Step 5: Simulation

In the DHM environment, the operator's postures, movements, and performed tasks are simulated.

Step 6: Ergonomic evaluation

Conducting evaluations of ergonomic indicators based on an in-depth analysis of all collected data and test results. Analysis of risk factors, risk level, and action categories. The action categories and action levels will provide key information and guidance on what risk factors (e.g., work posture, forces applied) are at an unacceptable level, as well as what degree of urgency for ergonomic intervention is required. If ergonomic indicators are unacceptable, this information is necessary to propose appropriate corrective solutions based on the investigated and identified root causes of the irregularities.

Step 7: Improvement

A proposed solution based on the above ergonomic analysis of the assessed workplace will enable achieving an acceptable level of ergonomic indicators.

Step 8: Verification and validation

Returning to the previous step of the framework to re-model and simulate tasks until a satisfactory level of ergonomic indicators is achieved.

Illustrative case study

Materials and methods

In order to illustrate the framework, a case study was developed for a typical stamping station equipped with a hydraulic press. In the presented case, the operator works in a standing position, stamping metal sheets. Ergonomic analysis was based on the Ovako Working posture Analyzing System (OWAS) method. Jack – Process Simulate Human Tecnomatix Siemens (academic version) was used for modeling and simulation.

OWAS method

The OWAS method was proposed by Finnish researchers (Karhu et al., 1977) to assess exposure to the risk of WRMSDs related to the operator's body postures. The method comprehensively addresses the issue based on the technique of observing an employee performing tasks. OWAS is based on the classification of 84 basic body postures, taking into account the position of the back, arms, and legs. Additionally, the external load in kilograms is considered, which gives a total of 252 possible combinations. Each of these combinations is a unique four-digit body posture code. For example, 2143 four-digit code: 2 – back bent forward; 1 – both arms below the shoulder joint; 4 – standing with legs bent; 3 – external load weighing over 20kg. The OWAS method focuses on identifying problems in the workplace and corrective actions, which are expressed in action categories (AC):

- AC1 – no risk, correct posture, no particular harmful effect on the operator's musculoskeletal system, no intervention is required.
- AC2 – there is little risk, the working posture has little harmful effect on the musculoskeletal system, and immediate intervention is not required, but ergonomic correction should be taken into account in the future.
- AC3 – high risk, the working posture has a significantly harmful effect on the musculoskeletal system; ergonomic intervention should be carried out as soon as possible.
- AC4 – very high risk, the working posture has a very harmful effect on the musculoskeletal system, and ergonomic intervention is required immediately.

Digital human modeling tool

Jack – Process Simulate Human Tecnomatix Siemens enables modeling of the workplace in a virtual environment, selecting of a 3D mannequin, simulation of postures and tasks performed, and assessing of ergonomic indicators (Human Centered Design and Simulation |Siemens Software).

Results and discussion

Steps 1, 2, and 3 allow selecting a workplace for evaluation. In this case study, a typical stamping station was analyzed. Studying the selected stamping station ensured gaining in-depth knowledge and collecting data about the task performed by the operator, the work process, workplace equipment, and their arrangement, etc.

Based on the data obtained in Step 4, the workplace was modeled in the DHM Jack virtual environment (Fig. 2).

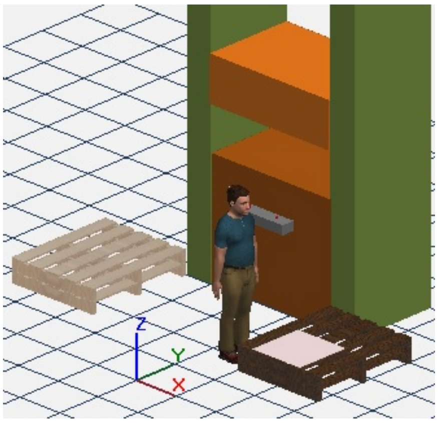

Fig. 2. Workplace before ergonomic intervention

The station is equipped with a hydraulic press, a pallet with metal sheets, and a pallet for placing stamped metal sheets. In the next 5th step, the operator's tasks, postures, and movements were simulated.

An ergonomic assessment was performed (Step 6). Critical indicators were found when the operator picked up a metal sheet from a pallet (Fig. 3). The OWAS code 2141 was received and classified as AC3 – high ergonomic risk; ergonomic intervention is required soon. The back was tilted forward (back position code 2), and the legs were bent in the knee joint (leg position code 4). The operator's incorrect posture was due to the pallet's too-low position with metal sheets.

The operation of placing and removing a metal sheet from the press was classified as AC1, OWAS code 1321

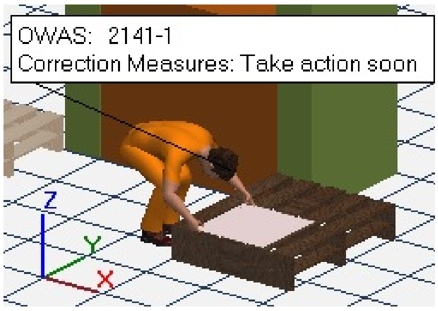

Fig. 3. Picking up a metal sheet from a pallet

(Fig. 4). Ergonomic risk was minimal, and no corrective action was required. However, it was noted that the arms were in a harmful position (both arms above the shoulder line – arm position code 3).

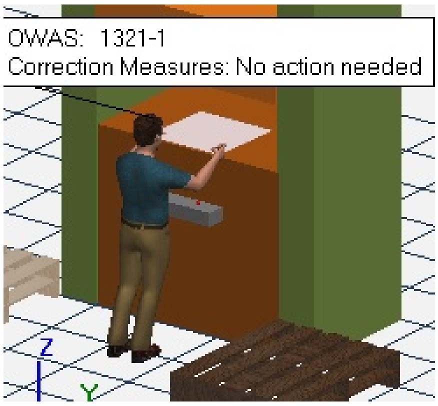

Fig. 4. Placing the metal sheet in the press

Irregularities were found relating to the operation of placing the stamped metal sheet on the pallet (Fig. 5).

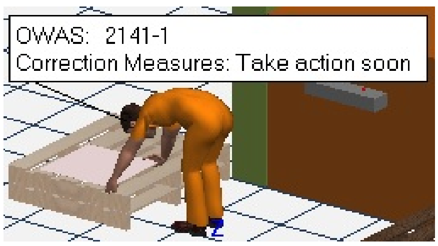

Fig. 5. Placing the stamped metal sheet on the pallet

The operator's body posture was harmful. The received OWAS code 2141 was classified as AC3 – high ergonomic risk; ergonomic intervention is required soon. The back was tilted forward (code 2), and the legs were bent in the knee joint (code 4). The reason for the operator's incorrect posture was the too-low position of the pallet.

The DHM Jack OWAS report on the pressing station confirmed the previous observations (Fig. 6, Fig. 7). Analysis of the report showed that a single work cycle lasted 24.3 seconds, and there were two main phases characterized by an action category value greater than 1. This means that these operations were associated with a WRMSDS risk greater than minimal. In turn, the results presented in Fig. 6 indicate that when performing stamping operations, the employee adopted postures that were not only uncomfortable (AC2) but also extremely harmful (AC3), which could lead to discomfort, fatigue, and a decrease in work efficiency.

The detailed results of the OWAS analysis for the tested workplace are presented in Fig. 7. The diagram shows the values of the action categories as a function of the task duration (in seconds) – a single cycle.

The level of ergonomic risk at the stamping workplace was not satisfactory enough because the operations of picking up metal sheets and placing stamped parts on a pallet created critical ergonomic problems. Actions have been taken to reduce the risk of WRMSDs. Consideration was given to increasing the height of the work plane for these two critical operations. Also taken into account was the critical posture of the arms when placing and removing the metal sheet from the press.

In the next stage, Step 7 Improvement was applied. A corrective solution was proposed in the form of placing pallets at the height of the employee's forearm and providing a platform for the operator.

To verify the proposed solution, Step 4 Modeling was used again. The proposed workplace changes in the virtual environment were modeled (Fig. 8).

In the next 5th step (Simulation), the task, postures, and movements of the operator were simulated using DHM Jack. Afterwards, an ergonomic assessment was performed (Step 6). The evaluation results for previous critical operations after corrective changes are shown in Fig. 9, 10, and 11.

In the case of picking up a metal sheet, the OWAS code 2121 was obtained (Fig. 9), and it was classified as AC2 – ergonomic intervention may be needed in the future. The ergonomic risk of WRMSDs has been reduced from high to medium.

Time (Sec)	Operation	Object Weight (kg)	Action Category	Code Posture Combination					
				Back	Arms	Legs	Load	-	Head
0	Go_to_target_Jack_Walk	0	1	1	1	2	1	-	1
0.03		0	1	1	1	7	1	-	1
0.87	Get_PartPrototype_Jack_Bend_And_Reach	0	1	1	1	2	1	-	1
1.17		0	2	1	1	4	1	-	1
1.2		0	3	2	1	4	1	-	1
3.27	Go_to_target_Jack_1_Arise_From_Bend	2.3	2	2	1	2	1	-	1
3.3		2.3	1	1	1	2	1	-	1
3.67	Go_to_target_Jack_1_Walk	2.3	1	1	1	3	1	-	1
3.7		2.3	1	1	1	7	1	-	1
3.8		2.3	1	1	1	7	1	-	5
3.83		2.3	1	1	1	7	1	-	1
4.33		2.3	1	1	1	2	1	-	1
4.67	Position_PartPrototype_Jack_Reach	2.3	1	1	2	2	1	-	1
4.7		2.3	1	1	3	2	1	-	1
4.73	Go_to_target_Jack_6_Walk	2.3	1	1	3	3	1	-	1
4.77		2.3	1	1	3	7	1	-	1
5		2.3	1	1	3	2	1	-	1
5.43	Go_to_target_Jack_2_Walk	0	1	1	1	3	1	-	1
5.47		0	1	1	1	7	1	-	1
5.6	Pose_Jack_Pose	0	1	1	1	2	1	-	1
8.63	Go_to_target_Jack_3_Walk	0	1	1	1	7	1	-	1
8.7		0	1	1	1	2	1	-	1
18.73	Go_to_target_Jack_7_Walk	0	1	1	1	7	1	-	1
19		0	1	1	1	2	1	-	1
19.37	Get_PartPrototype_Jack_1_Reach	0	1	1	1	3	1	-	1
19.53		0	1	1	3	2	1	-	1
19.7	Go_to_target_Jack_4_Walk	2.3	1	1	1	7	1	-	1
20.07		2.3	1	1	1	7	1	-	5
20.1		2.3	1	1	1	7	1	-	1
21.07		2.3	1	1	1	2	1	-	1
21.4	Put_PartPrototype_Jack_1_Bend_And_Reach	2.3	2	2	1	2	1	-	1
22.17		2.3	3	2	1	4	1	-	1
23.27	Go_to_target_Jack_5_Arise_From_Bend	0	2	2	1	2	1	-	1
23.93		0	1	1	1	2	1	-	1
24	Go_to_target_Jack_5_Walk	0	1	1	1	7	1	-	1
24.23		0	1	1	1	7	1	-	5
24.3		0	1	1	1	7	1	-	1

Fig. 6. Workplace simulation results (working times and OWAS ergonomics evaluation) – before ergonomic intervention

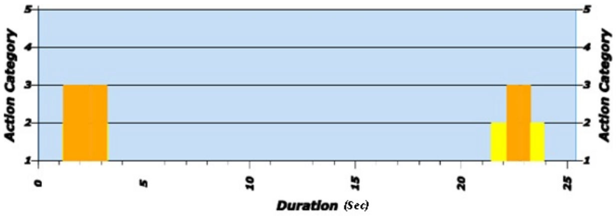

Fig. 7. OWAS action categories and critical operations before ergonomic intervention

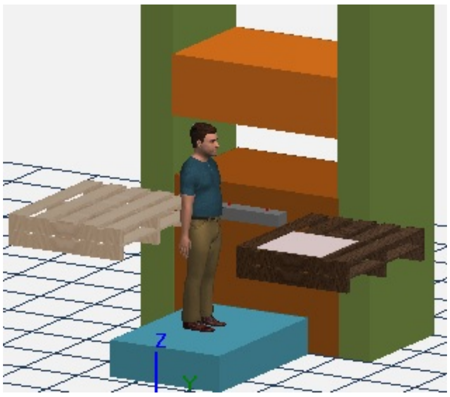

Fig. 8. Workplace after ergonomic intervention

Fig. 9. Picking up a metal sheet after ergonomic intervention

Unlike picking up a metal sheet, placing it in the press (Fig. 10) involves minimal ergonomic risk – AC1, no corrective actions are needed. The arm position code has been lowered from 3 to code 1 – both arms below the shoulders. Minimum risk and correct operator posture were achieved.

In turn, placing the stamped metal sheet on the pallet (Fig. 11) did not require the operator to adopt harmful postures. The OWAS code was correct: 1121; hence the operation was classified as AC1 – not requiring corrective actions. The action category was lowered from AC3 to AC1, and the WRMSDs risk level was lowered from high to minimal.

Following the DHM OWAS report by Jack, the proposed solution was implemented at the stamping station in the virtual environment and has been verified, so the results acquired earlier have been validated (refer to Fig. 12 and Fig. 13). The analysis conducted reveals an absence of any detrimental operator body postures (AC3 and AC4). The observations only report harmless categories of actions (AC1 and AC2).

Fig. 10. Placing the metal sheet in the press after ergonomic intervention

Fig. 11. Placing a metal sheet on a pallet after ergonomic intervention

The results of the OWAS analysis conducted for the stamping process after ergonomic intervention are shown in Fig. 12. The diagram presents the obtained action categories as a function of the duration of the stamping task (in seconds) – a single cycle. Only AC2 has been reported, lasting approximately 1.4 seconds. For the remaining time, the operator works in AC1 (Fig. 13).

It should be noted that a single work cycle before the ergonomic intervention lasted 24.3 seconds (Fig. 6), while the proposed solution allowed to shorten a single cycle to 23.17 seconds. This means a potential increase in work performance of 4.6%.

Time (Sec)	Operation	Object Weight (kg)	Action Category	Code Posture Combination Back	Arms	Legs	Load	-	Head
0	Get_PartPrototype_Jack_Walk	0	1	1	1	2	1	-	1
0.03		0	1	1	1	7	1	-	1
0.47		0	1	1	1	2	1	-	1
1.1	Get_PartPrototype_Jack_Bend_And_Reach	0	2	2	1	2	1	-	1
1.53		0	2	2	1	3	1	-	1
1.6		0	2	2	1	2	1	-	1
2.5	Go_to_target_Jack_Arise_From_Bend	2.3	2	2	1	3	1	-	1
2.53		2.3	2	2	1	2	1	-	1
2.6		2.3	1	1	1	2	1	-	2
3.23	Go_to_target_Jack_Walk	2.3	1	1	1	2	1	-	1
3.27		2.3	1	1	1	7	1	-	1
3.77	Position_PartPrototype_Jack_Reach	2.3	1	1	1	2	1	-	1
3.9		2.3	1	1	1	2	1	-	2
4.03	Go_to_target_Jack_1_Walk	2.3	1	1	1	3	1	-	1
4.07		2.3	1	1	1	7	1	-	1
4.3		2.3	1	1	1	2	1	-	1
4.9	Go_to_target_Jack_2_Walk	0	1	1	1	7	1	-	1
4.93		0	1	1	1	2	1	-	1
18.97	Go_to_target_Jack_3_Walk	0	1	1	1	7	1	-	1
19.13	Get_PartPrototype_Jack_1_Bend_And_Reach	0	1	1	1	2	1	-	1
21.77	Go_to_target_Jack_4_Arise_From_Bend	2.3	1	1	1	3	1	-	1
21.83	Go_to_target_Jack_4_Walk	2.3	1	1	1	7	1	-	1
21.9		2.3	1	1	1	7	1	-	5
21.97		2.3	1	1	1	7	1	-	1
22.47		2.3	1	1	1	2	1	-	1
22.77	Put_PartPrototype_Jack_1_Reach	2.3	1	1	1	2	1	-	2
22.93	Go_to_target_Jack_5_Walk	0	1	1	1	2	1	-	1
22.97		0	1	1	1	7	1	-	1
23.07		0	1	1	1	7	1	-	5
23.17		0	1	1	1	7	1	-	1

Fig. 12. Workplace simulation results (working times and OWAS ergonomics evaluation) – after ergonomic intervention

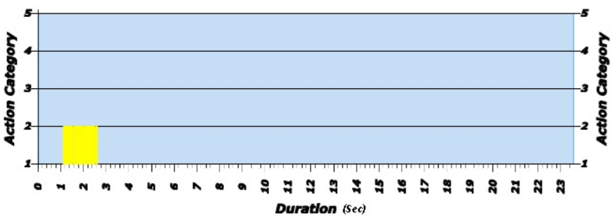

Fig. 13. OWAS action categories and critical operations after the ergonomic intervention

Conclusions

For companies to maintain high productivity and competitiveness in the market without endangering the health and safety of employees, it is necessary to improve workplaces in terms of ergonomic requirements. Verification of compliance with these requirements requires carrying out ergonomic assessments of workplaces. Currently, practitioners and ergonomists commonly perform WRMSDs exposure assessments using observational techniques. This requires the necessary knowledge and experience. Most often, such an assessment is based on observation and the ongoing recording of observations. These techniques require a lot of work time, and the final result depends to some extent on the subjective decisions of the evaluator.

The proposed methodological framework can support the activities of experts in the field of ergonomic research aimed at improving workplaces. DHM can provide satisfactory accuracy, and importantly, repeatability of measurements. Numerical models implemented in DHM allow the implementation of real-life situations. Moreover, and importantly, they enable ergonomic assessments not only of the static postures of operators but also of dynamic operations performed by employees, which ensures an objective assessment independent of the examiner.

The methodological framework presented in this study is easy to use in improving workplaces in terms of ergonomic requirements, as illustrated by a case study. All proposed solutions used to improve the ergonomic features of workplaces can be checked in the simulation process and their results will allow practitioners to choose the best solution to implement in the real workplace.

This study has limitations, as do most previous works. Data relating to the workplace must be collected and modeled in a virtual environment. The quality of the mapping will determine the size of the error between the virtual workplace and the real workplace. A motion capture system would be helpful; its use would shorten the time needed to simulate the task being performed. However, it should be pointed out that the motion capture system and DHM software are expensive and have their limitations.

Finally, the proposed methodological framework fits perfectly into the evolution of industry in the era of Industry 4.0 regarding the use of digital tools and software for the assessment of ergonomic indicators (Gladysz et al., 2023; Mgbemena et al., 2020). They also fit perfectly into Industry 5.0, where one of its fundamental pillars is a human-centric approach (Lu et al., 2022).

Future research could extend the studies of this paper. In an illustrative case study, a human model and the OWAS method were used. To extend the generalizability of the study, operators with different anthropometric characteristics (human models: a 5th and 95th percentiles) and sex, and different tasks performed by them could be examined. Other ergonomic indicators and methods could be considered, e.g., NIOSH manual lifting, energy expenditure, and RULA (David, 2005; Takala et al., 2010) for a deeper analysis of ergonomic risk factors and indicators related to the workplace. Also, the research could extend with further case studies based on stations involving the operator's manual work, e.g., assembly station, packaging station, semi-automatic spot-welding station with the participation of several expert ergonomist engineers to fully validate the proposed framework. A motion capture system could be included in the development of the methodological framework, which would provide more realistic results. Further research may also focus on extending the proposed framework to more complex systems, such as packaging and assembly lines.

References

Bartnicka, J. (2015). Knowledge-based ergonomic assessment of working conditions in surgical ward–A case study. *Safety Science*, *71*, 178–188. DOI: 10.1016/j.ssci.2014.08.010.

Battini, D., Faccio, M., Persona, A., & Sgarbossa, F. (2011). New methodological framework to improve productivity and ergonomics in assembly system design. *International Journal of Industrial Ergonomics*, *41*(1), 30–42. DOI: 10.1016/j.ergon.2010.12.001.

Bernard, B. P., & Putz-Anderson, V. (1997). Musculoskeletal disorders and workplace factors; a critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back.

Bernard, F., Zare, M., Sagot, J.-C., & Paquin, R. (2020). Using Digital and Physical Simulation to Focus on Human Factors and Ergonomics in Aviation Maintainability. *Human Factors*, *62*(1), 37–54. DOI: 10.1177/0018720819861496.

Cao, W. (2011). Ergonomic assessment of sonography workplace and posture parameters using digital human modeling. State University of New York at Binghamton.

Caterino, M., Rinaldi, M., & Fera, M. (2023). Digital ergonomics: An evaluation framework for the ergonomic risk assessment of heterogeneous workers. *International Journal of Computer Integrated Manufacturing*, *36*(2), 239–259. DOI: 10.1080/0951192X.2022.2090023.

Cieza, A., Causey, K., Kamenov, K., Hanson, S.W., Chatterji, S., & Vos, T. (2020). Global estimates of the need for rehabilitation based on the Global Burden of Disease study 2019: A systematic analysis for the Global Burden of Disease Study 2019. *The Lancet*, *396*(10267), 2006–2017. DOI: 10.1016/S0140-6736(20)32340-0.

David, G.C. (2005). Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders. *Occupational Medicine*, *55*(3), 190–199. DOI: 10.1093/occmed/kqi082.

DELMIA. (2023, January 27). Dassault Systèmes. https://www.3ds.com/products/delmia.

Emmatty, F.J., Panicker, V.V., & Baradwaj, K.C. (2021). Ergonomic evaluation of work table for waste sorting tasks using digital human modelling. *International Journal of Industrial Ergonomics*, *84*, 103146. DOI: 10.1016/j.ergon.2021.103146.

Estrada, J. E., & Vea, L. A. (2018). Modelling and Simulation of Spine in Sitting Posture in a Computer-Related Workplace. *Int. J. Comput. Sci. Mob. Comput*, *7*, 121–135.

European Agency for Safety and Health at Work. (2010). *OSH in figures: Work-related musculoskeletal disorders in the EU: facts and figures*. Publications Office. https://data.europa.eu/doi/10.2802/10952.

Feyen, R., Liu, Y., Chaffin, D., Jimmerson, G., & Joseph, B. (2000). Computer-aided ergonomics: A case study of incorporating ergonomics analyses into workplace design. *Applied Ergonomics*, *31*(3), 291–300. DOI: 10.1016/S0003-6870(99)00053-8.

Gladysz, B., Tran, T., Romero, D., van Erp, T., Abonyi, J., & Ruppert, T. (2023). Current development on the Operator 4.0 and transition towards the Operator 5.0: A systematic literature review in light of Industry 5.0. *Journal of Manufacturing Systems*, *70*, 160–185. DOI: 10.1016/j.jmsy.2023.07.008.

Grobelny, J., & Michalski, R. (2020). Preventing work-related musculoskeletal disorders in manufacturing by digital human modeling. *International Journal of Environmental Research and Public Health*, *17*(22), 8676. DOI: 10.3390/ijerph17228676.

Hamrol, A., Gawlik, J., & Sładek, J. (2019). Mechanical engineering in Industry 4.0. *Management and Production Engineering Review*, *10*, 14–28. DOI: 10.24425/mper.2019.129595.

Haynes, S., & Williams, K. (2008). Impact of seating posture on user comfort and typing performance for people with chronic low back pain. *International Journal of Industrial Ergonomics*, *38*(1), 35–46. DOI: 10.1016/j.ergon.2007.08.003.

Human centered design and simulation |Siemens Software. (n.d.). Siemens Digital Industries Software. Retrieved August 9, 2023, from https://plm.sw.siemens.com/en-US/tecnomatix/human-centered-design-simulation/.

Hussain, M.M., Qutubuddin, S., Kumar, K.P.R., & Reddy, C.K. (2019). Digital human modeling in ergonomic risk assessment of working postures using RULA. *Proceedings of the International Conference on Industrial Engineering and Operations Management, Bangkok, Thailand*, 5–7.

IEA. HFE definition. (2023). [The International Ergonomics Association]. https://iea.cc/about/what-is-ergonomics/.

Ji, X., Hettiarachchige, R.O., Littman, A.L., Lavery, N.L., & Piovesan, D. (2023). Prevent Workers from Injuries in the Brewing Company via Using Digital Human Modelling Technology. *Applied Sciences*, *13*(6), 3593. DOI: 10.3390/app13063593.

Kar, G., & Hedge, A. (2021). Effect of workstation configuration on musculoskeletal discomfort, productivity, postural risks, and perceived fatigue in a sit-stand-walk intervention for computer-based work. *Applied Ergonomics*, *90*, 103211. DOI: 10.1016/j.apergo.2020.103211.

Karhu, O., Kansi, P., & Kuorinka, I. (1977). Correcting working postures in industry: A practical method for analysis. *Applied Ergonomics*, *8*(4), 199–201. DOI: 10.1016/0003-6870(77)90164-8.

Lasota, A.M. (2014). Analysis of Packers' Workload on the Packing Line a Case Study. *LOGFORUM*, *10*(4), 383–392.

Lasota, A.M., & Hankiewicz, K. (2016). Assessment of risk to work-related musculoskeletal disorders of upper limbs at welding stations. In P. Arezas, J.S. Baptista, M.P. Barroso, P. Carneiro, P. Cordeiro, N. Costa, R. Melo, A.S. Miguel, & G. Perestrelo (Eds.), *SHO2016: International Symposium on Occupational Safety and Hygiene* (pp. 138–140). Portuguese Soc Occupational Safety & Hygiene.

Lasota, A.M., & Hankiewicz, K. (2017a). The conceptual framework for physical risk assessment in multipurpose workplaces. In N. Balc (Ed.), *Modern Technologies in Manufacturing (MTEM 2017—AMATUC)* (Vol. 137, p. 03007). EDP Sciences. DOI: 10.1051/matecconf/201713703007.

Lasota, A.M., & Hankiewicz, K. (2017b). The study of postural workload in assembly of furniture upholstery. *MATEC Web of Conferences*, *137*, 07002.

Lu, Y., Zheng, H., Chand, S., Xia, W., Liu, Z., Xu, X., Wang, L., Qin, Z., & Bao, J. (2022). Outlook on human-centric manufacturing towards Industry 5.0. *Journal of Manufacturing Systems*, *62*, 612–627. DOI: 10.1016/j.jmsy.2022.02.001.

Macdonald, W., & Oakman, J. (2022). The problem with "ergonomics injuries": What can ergonomists do? *Applied Ergonomics*, *103*, 103774. DOI: 10.1016/j.apergo.2022.103774.

Maurya, C.M., Karmakar, S., & Das, A.K. (2019). Digital human modeling (DHM) for improving work environment for specially-abled and elderly. *SN Applied Sciences*, *1*, 1–9. DOI: 10.1007/s42452-019-1399-y.

Mgbemena, C.E., Tiwari, A., Xu, Y., Prabhu, V., & Hutabarat, W. (2020). Ergonomic evaluation on the manufacturing shop floor: A review of hardware and software technologies. *CIRP Journal of Manufacturing Science and Technology*, *30*, 68–78. DOI: 10.1016/j.cirpj.2020.04.003.

Morag, I., & Luria, G. (2013). A framework for performing workplace hazard and risk analysis: A participative ergonomics approach. *Ergonomics*, *56*(7), 1086–1100. DOI: 10.1080/00140139.2013.790484.

Neumann, W.P., & Village, J. (2012). Ergonomics action research II: A framework for integrating HF into work system design. *Ergonomics*, *55*(10), 1140–1156. DOI: 10.1080/00140139.2012.706714.

Quiroz-Flores, J.C., Abásolo-Núñez, B., Suárez-Miñano, D., & Nallusamy, S. (2023). Minimization of Personnel Absenteeism with the Application of Proposed Ergonomic Model in a Plastics Manufacturing Industry. *Applied Sciences*, *13*(13), 7858. DOI: 10.3390/app13137858.

Radin Umar, R.Z., Tiong, J.Y., Ahmad, N., & Dahalan, J. (2023). Development of framework integrating ergonomics in Lean's Muda, Muri, and Mura concepts. *Production Planning & Control*, 1–9. DOI: 10.1080/09537287.2023.2189640.

SAMMIE CAD Ltd. (n.d.). Retrieved August 9, 2023, from https://www.lboro.ac.uk/microsites/lds/sammie/dhm.html.

Sanjog, J., Karmakar, S., Patel, T., & Chowdhury, A. (2015). Towards virtual ergonomics: Aviation and aerospace. *Aircraft Engineering and Aerospace Technology: An International Journal*, *87*(3), 266–273. DOI: 10.1108/AEAT-05-2013-0094.

SantosHuman Inc. (n.d.). SantosHuman, Inc. Retrieved August 9, 2023, from https://www.santoshumaninc.com/products/.

Schall Jr, M.C., Fethke, N.B., & Roemig, V. (2018). Digital human modeling in the occupational safety and health process: An application in manufacturing. *IISE Transactions on Occupational Ergonomics and Human Factors*, *6*(2), 64–75. DOI: 10.1080/24725838.2018.1491430.

Sickness absence in 2020. (2021). Social Security.

Spada, S., Germanà, D., Ghibaudo, L., & Sessa, F. (2017). Applications and benefits of digital human models to improve the design of workcells in car's manufacturing plants according to international standards.

Sun, X., Houssin, R., Renaud, J., & Gardoni, M. (2018). Towards a human factors and ergonomics integration framework in the early product design phase: Function-Task-Behaviour. *International Journal of Production Research*, *56*(14), 4941–4953. DOI: 10.1080/00207543.2018.1437287.

Taibi, Y., Metzler, Y.A., Bellingrath, S., & Müller, A. (2021). A systematic overview on the risk effects of psychosocial work characteristics on musculoskeletal disorders, absenteeism, and workplace accidents. *Applied Ergonomics*, *95*, 103434. DOI: 10.1016/j.apergo.2021.103434.

Takala, E.-P., Pehkonen, I., Forsman, M., Hansson, G.Å., Mathiassen, S.E., Neumann, W.P., Sjøgaard, G., Veiersted, K.B., Westgaard, R.H., & Winkel, J. (2010). Systematic evaluation of observational methods assessing biomechanical exposures at work. *Scandinavian Journal of Work, Environment & Health*, 3–24.

Tytyk, E. (2001). *Projektowanie ergonomiczne*. Wydaw. Naukowe PWN.

Wagner, D.W., Reed, M.P., & Rasmussen, J. (2007). Assessing the importance of motion dynamics for ergonomic analysis of manual materials handling tasks using the AnyBody Modeling System. *SAE Transactions*, 2092–2101.

Zink, K.J. (2014). Designing sustainable work systems: The need for a systems approach. *Applied Ergonomics*, *45*(1), 126–132. DOI: 10.1016/j.apergo.2013.03.023.