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MARIJA SAVKOVIĆ[1]
MARKO ĐAPAN[2]
CARLO CAIAZZO[3]
ALEKSANDAR BODIĆ[4]
ARSO VUKIĆEVIĆ[5]
IVAN MAČUŽIĆ[6]

[1,2,3,4,5,6]University of Kragujevac, Faculty of Engineering, Serbia

[1]marija.savkovic@kg.ac.rs
[2]djapan@kg.ac.rs
[3]carlocaiazzo@fink.rs
[4]abodic@uni.kg.ac.rs
[5]arso_kg@yahoo.com
[6]ivanm@kg.ac.rs

MULTIMODAL ANALYSIS OF WORKERS' COGNITIVE AND PHYSICAL STRESS

Abstract: *In the modern contemporary environment, simultaneous monitoring of physical and mental strain is very important in order to improve ergonomic conditions and the health of workers. This research paper presents a multimodal approach to assessing the physical and mental strain of workers during assembly activities. The proposed model combines the RULA (Rapid Upper Limb Assessment) method for assessing ergonomic risk and the EEG (electroencephalography) method for evaluating mental strain. Through an experimental study conducted on a sample of 7 subjects, the implications of assuming certain body postures on the physical and cognitive state of the subjects were analyzed.*

The results indicated a significant association between the adoption of non-physiological and non-ergonomic body postures and increased mental effort, which indicates the need for an integrated assessment when designing ergonomic workplaces. The results obtained showed that the application of ergonomic principles contributes to the reduction of physical and mental strain. The results also confirm that high levels of physical strain lead to changes in the brain activity of the subjects that correspond to increased mental effort. The proposed approach can serve as a basis for the development of advanced systems for monitoring and optimizing worker performance and well-being.

Keywords: mental strain, multimodal approach, ergonomic, physical strain, RULA

ORCID iDs:		
	Marija Savković	https://orcid.org/0000-0002-3620-7762
	Marko Đapan	https://orcid.org/0000-0002-8016-8422
	Carlo Caiazzo	https://orcid.org/0009-0007-2761-7886
	Aleksandar Bodić	https://orcid.org/0000-0002-1713-6540
	Arso Vukićević	https://orcid.org/0000-0003-4886-373X
	Ivan Mačužić	https://orcid.org/0000-0001-6153-6456

INTRODUCTION

In modern industrial systems, employees involved in assembling parts and components into a final product are increasingly exposed to physical and mental strain. Assembly tasks involve carrying out a sequence of precise and often repetitive operations, such as assembling parts, installing and positioning parts and components, testing, and final product adjustment. As such, assembly activities require a high level of attention and concentration, precision and coordination, as well as the ability to respond quickly to changing parameters in the production environment. These tasks can be both physically and mentally demanding, which necessitates the need to conduct ergonomic analyses and optimization in order to improve working conditions and increase productivity.

Holding unphysiological body postures for long periods of time and performing repetitive movements contribute to an increased risk of developing musculoskeletal disorders. On the other hand, mental overload and stress lead to a decrease in efficiency and effectiveness. Factors from the work environment can greatly affect the physical and mental ability of workers. For this reason, all ergonomic and organizational aspects need to be carefully considered in order to optimize working conditions, reduce the risk of work-related injuries and improve the efficiency of production processes. Traditional approaches to assessing workload often focus exclusively on one aspect - physical or cognitive - which can lead to an incomplete understanding of the real state. Therefore, there is a need for a multimodal approach to assessing the physical and mental workload of workers.

Physical and mental strain are two interrelated aspects that significantly impact the efficiency, health and well-being of employees. Although they are often viewed separately, numerous studies show that there is a clear correlation between physical exertion and increased mental strain, especially in conditions where work activities require a high degree of concentration, attention and coordination. Physical strain can lead to mental fatigue, reduced attention and an increased tendency to make mistakes, which directly affects worker performance. On the other hand, intense mental strain can intensify the experience of physical strain, even when objective physical demands are low. This psychophysical interaction often leads to a deterioration in the health of workers, which indicates the need for a holistic approach to workplace design.

In this regard, there is a need for a multimodal approach that combines different measurement and assessment methods, in order to cover all dimensions of the load. In this paper, the multimodal approach is based on the application of the RULA method for assessing the ergonomic risk of musculoskeletal disorders and the EEG method for monitoring the mental state of workers in real time during the execution of an assembly task.

The aim of the research paper is analysis of data obtained by a combination of these methods to show the connection between the adoption of certain body postures and mental effort during assembly activities. The paper points to the importance of applying ergonomic principles when designing workplaces, optimizing the work environment and adapting working conditions to the needs of workers in order to reduce the physical and mental burden of workers, eliminate injuries at work and improve the general health and satisfaction of workers.

PROBLEM STATEMENT

Despite the growing trend of automation and the application of advanced Industry 4.0 technologies, in numerous modern industrial workplaces, full digitalization is not achievable, resulting in the continued reliance on repetitive and monotonous manual assembly tasks.

Assembly activities at industrial workstations are most often performed in ergonomically inadequate and non-physiological body postures for a long period of time, which leads to the occurrence of occupational diseases, most often musculoskeletal disorders, including carpal tunnel syndrome, tendonitis, etc. (Barr et al., 2004). Frequent performance of repetitive movements and performance of movements at high speed in non-physiological body postures for a long period of time increases the load on the tendons, muscles and nerves of the hand, joints of the forearm muscles and neck muscles, which further causes strain and pain in the muscles of the upper extremities.

The main risk factors for the development of musculoskeletal disorders in the literature are non-physiological body posture and inadequately designed workplace (Petreanu & Seracin, 2017). Also, given the frequent performance of repetitive activities, which leads to a decrease in attention and concentration, workers are exposed to mental strain and are more prone to making mistakes. In some situations, workers repeat the same work operation several thousand times during a work shift, which causes mental fatigue.

Mental strain is one of the most commonly used concepts in ergonomics and human factors and is a topic of increasing importance. As modern technology imposes ever-increasing cognitive demands, understanding the impact of mental strain on worker performance and well-being is increasingly important (Young et al., 2015). There is a growing need to investigate the causal relationship between physical and mental strain, especially in work environments where workers are exposed to high demands.

Mental workload is the level of cognitive effort a person puts into performing work tasks. Carrying out assembly tasks requires maintaining a high level of attention and concentration, focusing on work operations, remembering information, making decisions, and solving problem situations. Mental workload occurs when the demands of work tasks exceed or approach the cognitive capacities of the worker.

Mental strain depends on several factors - the complexity of work tasks, the duration of the activity, the work experience, motivation, and also the physical condition of the organism. Mental strain can negatively affect performance, lead to a decrease in productivity and efficiency, and an increase in the number of errors. Therefore, recognizing and monitoring mental strain is of great importance for effective workplace design, especially during tasks that require a high level of concentration and attention.

Lean philosophy is a modern approach to organizational management, derived from the Japanese Toyota Production System (TPS), aimed at the rational use of resources (time, space, effort) and the production of quality products that meet customer needs. In the lean concept, the focus is on performing only those activities that add value and eliminating all forms of loss and unnecessary waste. All activities that do not directly contribute to the creation of value for the end user are considered losses in the context of lean philosophy. According to (Suzaki, 1987), everything except the minimum amount of equipment, materials, parts, space and the minimum expenditure of employee time required to produce the necessary products is considered waste.

Special emphasis is placed on continuous improvement of the work process, redesigning workplaces and adapting to the individual characteristics of workers. In the context of ergonomics, the application of the lean concept involves improving workplaces in order to eliminate all problems that arise due to the inefficient arrangement of necessary parts, components, and tools, adopting non-physiological body postures, performing unnecessary movements, reducing physical and cognitive load, etc. (Santos et al., 2019).

The importance of incorporating ergonomic principles when designing a work environment in which repetitive assembly tasks are performed is also indicated by numerous scientific research papers (Neumann et al., 2002). The main goal of applying ergonomic measures is to tailor the work, tasks, and equipment to suit the needs of the workers through modification of the work environment, and equipment, and through minimizing poor posture and excessive muscle strain, in order to improve performance, reduce work injuries, and occupational diseases.

The RULA method is one of the most commonly used tools for assessing ergonomic risks related to upper body loads during work activities. This method allows for the quick and efficient identification of unfavorable positions and movements that can lead to musculoskeletal disorders. In the modern approach to ergonomics, digital modeling of working positions and movements is increasingly being applied as it enables detailed simulation and analysis in a virtual environment. Combining the RULA method with software solutions for digital modeling allows for more precise and comprehensive assessments of work processes, which contributes to the improvement of working conditions and the prevention of occupational injuries and occupational diseases.

Mental strain can be measured indirectly (via subjective questionnaires), by monitoring performance, or by analyzing physiological parameters such as electroencephalography (EEG). Modern research is increasingly focusing on multimodal methods of monitoring mental strain, in which objective data obtained through the application of psychophysiological methods are combined with subjective assessments, to gain a more comprehensive understanding of workers' cognitive strain.

The application of methods from the domain of neuroergonomics allows for deeper insight into the mental workload of workers (Ayaz & Dehais, 2019). As the authors point out (Trimmel et al., 2009), psychophysiological methods allow for objective quantification of cognitive state in real time. Monitoring brain activity provides insight into how people think, process information, solve problems, and make decisions in different situations (Gevins et al., 1995). This allows for monitoring changes in brain waves when a worker moves from simple to more complex cognitive tasks, helping to evaluate the mental effort required to complete work activities.

METHODOLOGY

In this research paper, a multimodal approach to assessing the physical and mental strain of workers while performing assembly activities is presented. The proposed model combines the RULA (Rapid Upper Limb Assessment) method for assessing ergonomic risk and the EEG (electroencephalography) method for evaluating mental strain.

The research conducted is based on an interdisciplinary approach that integrates ergonomic aspects, methods from the field of industrial engineering, and modern innovative technologies of Industry 4.0.

A total of 7 respondents participated in both scenarios. The respondents were undergraduate, master's and doctoral students at the Faculty of Engineering Sciences, University of Kragujevac, male, right-handed, aged between 18 and 30.

Experimental research was conducted in two scenarios: non-ergonomic and ergonomic. In a non-ergonomic scenario, the research was conducted on a traditional workstation, which was not aligned with ergonomic and lean principles. In the ergonomic scenario, the research was conducted on a proposed new workstation, designed in accordance with the "golden zone" standards, 5S, and ergonomic principles. The experimental procedure is described in detail in the research paper (Savković et al., 2023).

For the purpose of conducting complex research during the simulation of assembly tasks in the laboratory of the Faculty of Engineering of the University of Kragujevac, an industrial assembly workstation was designed and developed, which is aligned with ergonomic and lean principles and golden zone standards.

Industrial practice in this area reminds the organization of the importance of introducing ergonomics measures when designing installation workstations (Anghel et al., 2019). Designing assembly workstations requires careful consideration of the physical and cognitive abilities and limitations of workers. Special focus is placed on analyzing anthropometric characteristics, arm reach, and body posture to reduce physical strain and minimize the potential for work-related injuries (Figure 1.).

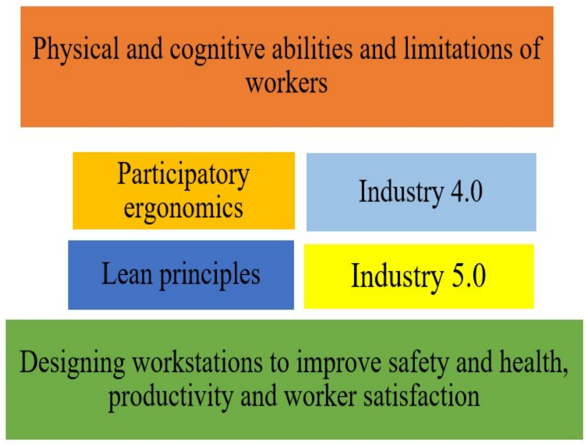

Figure 1. *A comprehensive approach to workstation design in accordance with ergonomic and lean principles*

Safety 4.0 represents a shift towards an approach to workplace safety based on big data analysis and the application of innovative technologies. In the context of Industry 4.0, a human-centered workplace is one that involves the application of advanced technologies in a way that assists workers in performing work activities rather than replacing them. In the era of Industry 4.0, ergonomics is of particular importance. The emphasis is on adapting advanced technologies to the needs and abilities of people and optimizing the interaction between people and other elements of the work system.

Industry 5.0 promotes a human-centered approach and places the worker at the center of production processes (which is represented in scientific research papers through the term Operator 5.0), with special attention paid to increasing their safety, health, satisfaction, and well-being at work (Aromaa et al., 2018).

Participatory ergonomics involves involving workers in the process of designing and improving the work environment. Respondents, in accordance with individual requirements and needs, provided direct information related to improving the workplace, tools and equipment, which contributed to reducing strain and increasing safety.

The new modular assembly workstation is displayed in Figure 2.

Figure 2. *Proposed modular workstation*

Unlike a traditional workstation, the new workstation is designed with ergonomic principles and the 5S principles in mind, and in accordance with the golden zone standards, taking into account the fact that the zones of the working space are different for each person (Savković et al., 2022). The proposed workstation is fully adapted to the worker's anthropometric characteristics, needs, abilities and limitations, thereby reducing bending and stretching of the body. At the proposed assembly workstation, the subjects performed work tasks within the golden zone. As a result, unnecessary movements such as reaching, stretching, and bending were reduced because all materials, components, and tools were positioned at waist level.

The RULA method and the EEG method were applied in the experimental research. The RULA method was used to assess physical strain. Using a combination of the RULA method and computer modeling, the workplace, work activities, and body movements and postures were analyzed, as well as the application of force, in order to determine which factors contribute to muscle strain, or which risk factors contribute to the development of musculoskeletal disorders.

RULA is one of the most cited and commonly used methods for assessing ergonomic risk in the workplace (McAtamney & Corlett, 1993).

A certain number of points is assigned for each body posture taken by the respondents. The scores obtained using the RULA method range from 1 to 7:

- Grades 1 and 2 indicate that the posture is considered acceptable if it is not maintained or repeated over a long period of time. These grades indicate that there is no significant risk of developing musculoskeletal disorders.
- Grades 3 and 4 (yellow): These grades indicate that further research is needed. Changes in the way work tasks are performed or in the work environment may be necessary in the future to reduce ergonomic risks.
- Grades 5 and 6 (orange) indicate an increased risk of occupational diseases, which means that changes need to be introduced in the near future. The current working conditions in which assembly activities are carried out can lead to serious health problems if changes are not introduced.
- A score of 7 (red) indicates the urgency of taking ergonomic measures to change working conditions in order to prevent musculoskeletal disorders and other occupational diseases.

Brain activity was monitored using electroencephalography during the assembly tasks. EEG is one of the most commonly used methods for measuring electrical brain activity in real time (Hogervorst et al., 2014).

Recently, the EEG method has been increasingly used in industrial environments, in ergonomics, in monitoring brain activity, assessing the cognitive state and mental load of workers, and determining whether a worker can maintain attention for a longer period of time (Infantolino & Miller, 2014). The authors (Gevins et al., 1995) believe that this method is particularly useful in measuring brain activity in workplaces that require high concentration from workers. This method allows the detection of subtle changes in mental state that are not necessarily visible to external observation.

An EEG cap with 24 electrodes was placed on the subject's head to measure the action potential of neurons. Brain activity was monitored in the frontal (AFz, Fz, Fp1, Fp2, F3, F4, F7 and F8), central (Cz, CPz, C3 and C4), temporal (T7, T8), parietal (CPz, Pz, P3, P4, P7, P8) and occipital (O1 and O2) regions and the midbrain region (M1 and M2). A SMARTING wireless 24-channel EEG system with a triggering frequency of 250 Hz was used to record the EEG signal. The EEG cap was connected to a mobile Smarting amplifier from mBrainTrain LLC (Belgrade, Serbia) with dimensions of 85 × 51 × 12 mm and a weight of 60 g.

RESULTS AND DISCUSSION

The results of the RULA analysis during assembly activities in a non-ergonomic scenario are shown in Figure 3. As can be seen in the figure, since at a traditional workstation the necessary components, parts and tools were not placed and arranged in accordance with the golden zone, lean and 5S principles, the subjects were forced to bend and stretch their bodies in order to reach them. Therefore, the total RULA analysis result for this position is 7, which is the maximum value and indicates that additional research and changes should be carried out immediately. A particular problem was the very limited possibility of changing the body posture during the work activity.

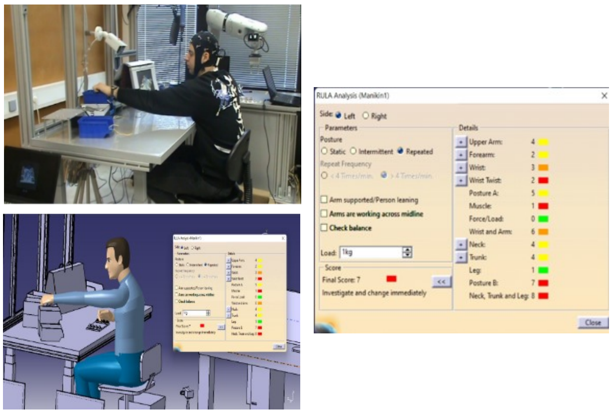

Figure 3. *Results of RULA analysis - non-ergonomic scenario*

At the new workstation, all necessary objects, materials and components were arranged and adapted to the needs, requirements and individual characteristics of the subjects, as shown in Figure 4. These changes contributed to the result after the RULA analysis for this position being 3 (which is a significantly lower value compared to the scores obtained in the non-ergonomic scenario). The subjects did not stretch their bodies to reach the necessary wires as in the non-ergonomic scenario because the cluster with wires was placed within the golden zone, and this significantly contributed to reducing the risk of developing musculoskeletal disorders.

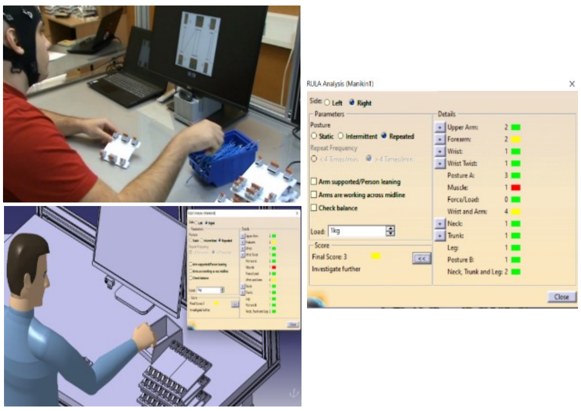

Figure 4. *Results of RULA analysis - ergonomic scenario*

The results of monitoring the mental workload of all 7 respondents using the mental workload index (MWLi) in non-ergonomic scenarios as shown in Figure 5.

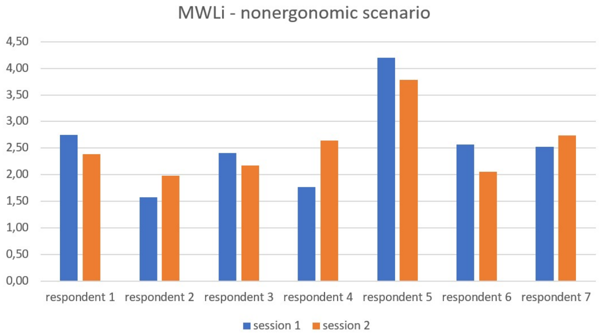

Figure 5. *Results of brain activity monitoring using the MWLi index in a non-ergonomic scenario*

Figure 6 presents the preliminary results of monitoring mental strain in an ergonomic scenario. The histogram does not show the results for respondent 2 in the first session due to technical reasons.

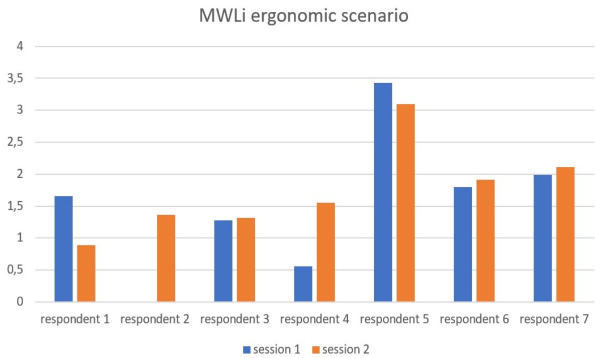

Figure 6. *Results of monitoring brain activity via the MWLi index in an ergonomic scenario*

As can be seen from the histogram, higher index values were recorded in the non-ergonomic scenario compared to the ergonomic scenario. The increased value of the MWLi index in the non-ergonomic scenario indicates that they are exposed to increased mental strain. The results showed that occupying static body postures for a longer period of time, performing repetitive movements, or performing activities in non-physiological body postures leads to a significant increase in mental strain. The reason for this can be found in the respondents' efforts to maintain concentration and accuracy despite physical exertion, which requires additional engagement of cognitive resources and causes mental fatigue. On the other hand, adapting the workplace to the respondents, by optimally organizing equipment, tools, and components based on their anthropometric and biomechanical traits contributes to reducing mental strain.

The obtained results indicate a significant correlation between physical and mental strain during assembly activities. The high value of the RULA analysis results in the non-ergonomic scenario indicates that the subjects performed activities in an unfavorable and static body posture, which can lead to the development of musculoskeletal disorders if appropriate ergonomic measures are not taken.

The results showed that in the non-ergonomic scenario, the subjects were exposed to greater physical strain due to inadequate organization of the workspace, adopting inadequate body postures, and performing non-ergonomic movements because the tools, parts, and components required for assembly were placed on the work surface outside the subject's maximum reach zone. Frequent bending of the torso, bending of the neck and limited body mobility further contributed to the increase in physical strain in each subject. At the same time, in the non-ergonomic scenario, the subjects were exposed to greater mental strain compared to the ergonomic scenario, as shown by the results obtained by the EEG method. Results show that factors from the external environment greatly disturbed the respondents while performing assembly activities in a non-ergonomic scenario, which contributed to an increase in mental strain.

On the other hand, in the ergonomic scenario, the effects of these unfavorable factors were eliminated, which led to a significant improvement in working conditions. The optimal organization of the workspace and the elimination of external distractions resulted in a reduction in the physical and mental burden of the respondents. The results obtained clearly confirm the importance of applying ergonomic principles in workplace design.

CONCLUSION

Workers performing assembly activities at traditional workstations in real-world industrial environments are exposed to musculoskeletal disorders and other occupational diseases. Musculoskeletal disorders can occur as a result of adopting non-physiological body postures, performing repetitive movements, or chronic strain and overload, leading to pain, swelling, stiffness, and reduced functionality. Also, during the assembly of parts and components, workers are exposed to fatigue due to reduced attention and concentration.

This research paper presents a multimodal approach to the analysis of physical and mental strain of workers, combining the RULA method for assessing body position and the EEG method for monitoring brain activity. The results indicated that the subjects were exposed to high physical and mental strain when performing assembly activities in a non-physiological body posture in a non-ergonomic scenario. This was confirmed by a maximum RULA score of 7, as well as significant cognitive strain during task execution in the non-ergonomic scenario compared to the ergonomic scenario, as indicated by elevated mental strain index values.

The results obtained indicate the need for a systematic approach to load assessment that includes both physical and mental aspects. The results of the experimental research represent the basis for further ergonomic improvement of assembly workstations and the improvement of working conditions in order to prevent occupational diseases and increase the efficiency of production processes.

Future research should include different types of work tasks, as well as long-term monitoring of the effects of ergonomic measures, with the aim of developing personalized strategies for optimizing working conditions.

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