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Assessment of the Effectiveness and Safety of Exoskeletons in Industrial Workplaces

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ABSTRACT

Machinery safety requirements are based on legislation and recommendations of harmonized standards (e.g. Directive 2006/42/EC, ISO 12100). A key aspect is the risk assessment, which considers the impact of hazardous situations and hazardous events on human lives and health. Risk analysis and assessment has traditionally been methodically supported by various tools, as Risk Matrix, Risk Graph, Failure Cause and Effect Analysis (FMEA), etc. A major problem in terms of meeting legal requirements is the assessment of exposure by factors such as noise, vibration and, in particular, the physical strain resulting from handling loads. Modern robotic workplaces are created by connecting several machines. On the positive side, high-risk hazardous situations (zones) are eliminated or minimized for the person working in such workplace. However, human activities are thus limited in particular to handling tasks, product quality control and withdrawal of finished products. Here, such influences arise that can affect human health in the long term, resulting from muscular load, which depends mainly on the design of the workplace, that means taking into account ergonomic principles already within workplace design. Measuring the physical load allows to “set up” the workplace so that the load is both immediate and long-term reduced by a suitable design solution, or by technical devices that reduce this load. Recently, research has focused on personalizing the reduction of musculoskeletal load not only by changing the workplace, but also by developing and testing special devices called exoskeletons. Exoskeleton’s interface is important to improve comfort, performance and of course personal health.

Keywords: Ergonomics, Risk assessment, Exoskeleton, Human health prevention, Physical load, Work-related musculoskeletal disorders

INTRODUCTION

Damage to the musculoskeletal system is one of the most common work-related disorders. Recent research indicates that work-related musculoskeletal disorders (WMSDs) are one of the major health problems in the workplace, also with significant economic impact (Sultan-Taïeb et al., 2017), (Bevan, 2015). They affect millions of employees across Europe and represent a cost in billions of euros for employers. Dealing with musculoskeletal disorders helps to improve the lives of workers, but it also makes business perspective.

The innovation potential in digitization and meeting growing demand, increase in productivity is wide ranging from increasingly sophisticated robots replacing workers in customer-oriented roles, to additive manufacturing technologies (3D printing) producing human organs (Costantino et al., 2021). The adoption of automation in industry has been growing over the last twenty years, intending to increase productivity while reducing the physical workload required for human workers (Pacaiova et al., 2021). Also, according to OSHA (Occupational Safety and Health Agency), (Onofrejova et al., 2021), and the implementation of robotics and exoskeletons, could also contribute to the improvement of working conditions. Pons (Pons et al., 2008) describes that the topic of exoskeletons is widely presented, including biomechatronic design, cognitive and physical human-robot interactions, wearable robotic technologies, kinematics, dynamics, and control. New body-worn assistive devices - occupational exoskeletons (Theurel and Desbrosses, 2019) have been introduced in some workplaces to help workers performing manual manipulation tasks while reducing the load on the muscular system (Pesenti et al., 2021). Currently, the interest in exoskeleton research has expanded into several areas. In particular, it has recently transferred from the medical/rehabilitation field to the industrial sector. This is due to several reasons. On the one hand, the development of rehabilitation exoskeletons could reach a plateau because reliable and efficient solutions are available for these applications. On the other hand, Industry 4.0 is moving towards the concept of smart factories.

Many upper- and lower-limb wearable exoskeletons, which are mechanical structures worn on the body to enhance the strength of the wearer, have been developed and studied for their potential effect to limit exposure to physical load (DeLooze et al., 2015). Moreover, kinematics, postural control, and discomfort in passive, lower-limb exoskeleton was studied in (Luger et al., 2019). Types of exoskeletons can be classified according to five criteria, which are: 1. what part of the human body the exoskeleton is designed for; 2. what element the exoskeleton is driven by; 3. how the exoskeleton is fixed; 4. how the exoskeleton is controlled; and, 5. what the exoskeleton is composed of.

Currently, most studies on exoskeletons demonstrate promising results. Authors (Maurice et al., 2019) investigated the PAEXO passive exoskeleton for overhead work, the use of which effectively reduces physical effort and fatigue. Authors (Veslin et al., 2012) focused on the study of the upper arm exoskeleton and created a simulation in Matlab. Other study (Steinhilber et al., 2020) indicates that lower extremity exoskeletons, aiming to reduce physical load associated with prolonged standing, may impair workers' postural control and increase the risk of falling. According to (Zampogna et al. 2020), and other studies about wearable technology (Teng et al., 2008), (Khakurel, et al., 2017) has been proving convincing and useful results in evaluating motor impairments of subjects suffering from (among others) Parkinson disease. Other studies argue that exoskeletons need to be closely linked to the manufacturing activities of Industry 4.0 organizations (Kadir and Broberg, 2021) as they will perform operations in collaboration with these advanced technologies (Onofrejova and Simsik, 2019). Authors (Maurice et al., 2018) in the study examined the opinion of factory workers and non-workers on three human-centered technologies aiming at improving working conditions: collaborative robots, exoskeletons and wearable sensors. Workers and non-workers were mostly positive about these technologies and agreed they would increase workers' physical well-being. Not many studies have investigated poor mental well-being in the workplace due to work-related musculoskeletal disorders (Maakip et al., 2017). In the automotive industry, they investigated the Noonee chairless-chair, which is a passive device for workers that does not require power. It is supposed to be a practical device for workers who have to remain in ergonomically uncomfortable positions.

ERGONOMIC DESIGN OF WORKPLACE SUPPORTED BY SENSOR MEASUREMENTS AND EXOSKELETON DEVICES

Here, such influences arise that can affect human health in the long term, resulting from muscular load, which depends mainly on the design of the workplace, that means taking into account ergonomic principles already at workplace and machinery design. Ergonomic risk assessment principles require such risks assessment coming from load handling, work tools, lighting, ventilation, workplace noise, vibration from work equipment and other stressors. Quantitative measurement of physical activity based on standard criteria (e.g., ISO 6385, ISO/TS 20646, ISO 11228-1, 11228-2) requires the application of a suitable measurement system. Measuring the physical load allows to "set up" the workplace so that the load is both immediate and long-term reduced by a suitable design solution, or by technical devices that reduce such load.

Recently, research has focused on personalizing the reduction of musculoskeletal load not only by changing the workplace, but also by developing and testing special devices called exoskeletons. Exoskeletons interface are required to improve comfort and usability. However, some authors claim (Theurel and Desbrosses, 2019) that laboratory-based evaluations of exoskeletons justify different results, since the effect of an exoskeleton is task specific and they cannot be used as a basis for a decision on the universal application of the exoskeleton in practice. Perceived use of an exoskeleton, whether the exoskeleton is being safe or dangerous and the potential risks of wearing an exoskeleton have to be known prior to their application in the workplace. However, exoskeletons can have the unintended negative consequence of reducing human flexibility leading to new sources of musculoskeletal disorders (MSDs) and accidents. The three main risks can be identified, as getting caught by objects in the work environment, a risk of falling, and a concern for developing new musculoskeletal disorders, or muscular atrophy.

Some linkage is important to assess the risks associated with the activity and to reassess the risks following the application of the exoskeleton. The basic principle is that exposure to the workload must consider all risks and especially their long-term effects on the worker and verify whether such equipment (exoskeleton) reduces these risks or can be a source of new hazards to

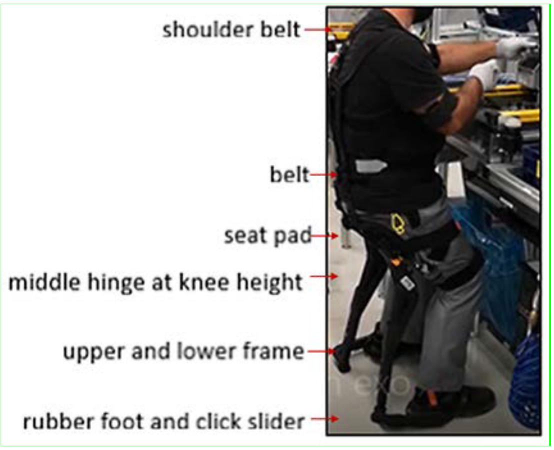


Figure 1: Lower body exoskeleton – Chairless chair 2.0 (CC 2.0). Exoskeleton was used in Experiment 2 (EXO): minimizing the physical load by ergonomic sit-stand pattern.

the activity. The methodology of risk assessment in practice requires a change of approach in its application in a particular work environment and even a certain modification considering the qualitative and even quantitative effects of stress factors in the use of the exoskeleton.

Measurement Design

Our trial field experiment is based on comparing the occupational conditions of workers in two states: a) standard work in standing position [STAND] (E_{N_A}); b) work with technical device – exoskeleton in standing/sitting position [EXO] (E_{W_A}). The introductory measurements were set in industrial workspace, where the worker's job was to assemble the mounting nest by placing the outer and inner ring there, as well as inserting a metal stones into the marked holes in takt of 0.94 minutes. Synchro pre-assembly consists of 10 tasks, in each task handles 1 piece; mean manipulation time (TM_{mean}) for manipulation per 1 piece is ~ 0.09 min. Particular assembly workplace with repetitive movements was chosen for exoskeleton deployment. The working height is solid with "elbow-floor" distance d_{ef} equal to 1.22 m and working distance "grasping arm" (sagittal plane) d_{ga} equal to 0.23 m. Workplace design couldn't been changed during experiment and we intended to investigate, whether existing workplace is suitable for diverse group of workers, if there are any insufficiencies and the workplace posing a risk of developing MSDs to the employees. The workers as end-users were trained with safety instructions on the use of the exoskeleton CC 2.0. The training was performed a day before experiments were conducted, and lasted ~ 30 minutes for each tested worker. The duration of one experiment was ~ 30 minutes. As a corrective measure, the industrial exoskeleton CC 2.0 was applied, as a support of lower body part.

The Chairless Chair® 2.0 (CC 2.0) (Figure 1) is a Wearable Ergonomic Mechanical Device intended for use in production and assembly lines. It allows users to take breaks and sit down occasionally while working.

Table 1. Verification of measured motion data file normality is performed using the Shapiro-Wilk normality test. For each file we tested the null hypothesis: "The sample distribution is normal". If the p-value is less than the significance level α, then the null hypothesis is rejected and the distribution is non-normal.

Joint/Mean $\bar{x}$ [%]	Green Area		Orange Area		Red Area	
Condition	STAND	EXO	STAND	EXO	STAND	EXO
Neck	55.5	66.7	34.1	26.7	10.4	6.5
Lower Back	93.1	95.9	6.8	4.1	0.1	0.0
Right Shoulder	72.8	72.0	18.6	19.0	8.6	9.0
Left Shoulder	77.7[1]	61.1[1]	15.9[1]	26.7[1]	6.4	8.6
Right Hip	94.6	83.7	5.4	8.0	0.0	8.2
Left Hip	89.7[1]	72.8[1]	10.1[1]	21.0[1]	0.2	6.2[1]

[1] Values with significant impact on results.

Occupational exoskeleton was used in Experiment 2 (EXO) as a technical aid for improving the ergonomic postures of the worker and applying sit-stand pattern at work. Experiment 1 (STAND) preceded Experiment 2 (EXO) and served to measure the actual state of ergonomic workload of the worker.

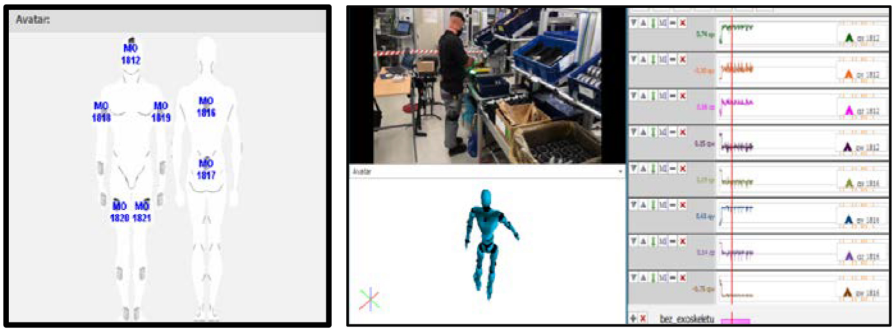
For the assessment of the ergonomic risk, the wireless sensor ergonomic system TEA Captiv was used. Captiv enables an adaptable and scalable solution for capturing workers in their work environments thanks to a multifunctional analysis embodying body posture, carrying capacity, musculoskeletal limitations and repetitive movements and vibrations. The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of the Technical University of Kosice (protocol code 8268/2021/R-OLP).

The measured data were displayed via 3D avatar (virtual human mannequin), which offered animations of the provided task together with visualizations of system evaluation results by marking body segments with green/orange/red colors indicating fully customizable threshold values for reference angles. Green color means suitable conditions for a segment loading; orange indicates a change in activity has to be considered, and red indicates inappropriate activity that needs an immediate correction.

Figure 2a shows the placement of 7 motion sensors (MO) on the following segments: Head (forehead), Back (spine on T2), Pelvis, Left and right arms (humerus), Left and right forearms (radius, cubitus), Upper left and right legs (femur). The Captiv's avatar represents worker activity, and his simultaneous joints angles with colors indicating which threshold values exceeded in the monitored joints, see Figure 2a and 2b, and Figure 3a and 3b.

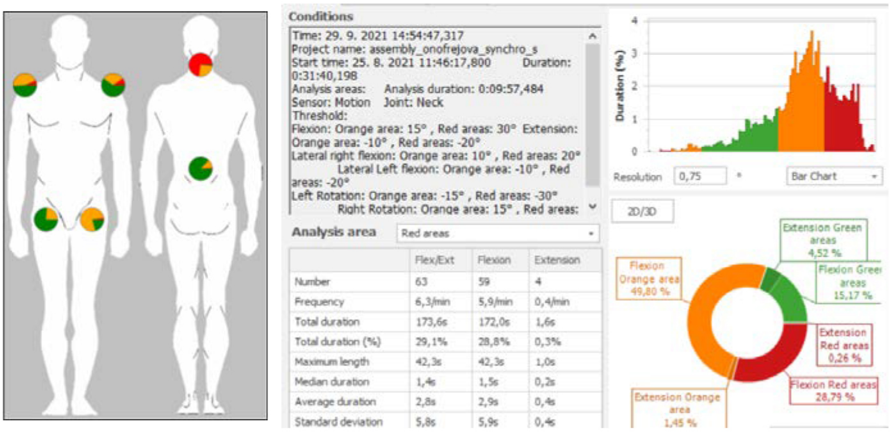
CONCLUSION

We used the wireless sensor system Captiv for ergonomic risk assessment at the assembly workplace in the automotive industry in our first experiments with 7 motion sensors. Our tested workers repetitively performed assembly of synchronous units in the transmission in the fast pace. Measurement results indicated the unacceptable ergonomic risk in the neck, shoulder



(a) (b)

Figure 2: Setting and the implementation of the measurement in the industrial workspace: (a) Placement of the Captiv wireless sensors on the body; (b) The captured data with Captiv sensor system before their evaluation, with synchronization of data and video recording, and avatar visualization.



(a) (b)

Figure 3: Results: a) Postures evaluation results for work activity; b) Detailed results of time duration in individual postures, in experiment with 1 worker using exoskeleton for neck flexion/extension.

and hip joints. To eliminate the physical load, the employee was applied a passive exoskeleton CC 2.0, which is designed to support the lower limbs. Improvement of the posture is evident in the upper body. Results from our trial measurements show positive impact on the workers when using exoskeleton; there is evident improvement in the position of workers, in flexion of neck the ratio (%) between zones green/orange/red was changed from 55.5/34.1/10.4 to 66.7/26.7/6.5; lower back was without significant changes, the ratio (%) between zones green/orange/red was changed from 93.1/6.8/0.1 to 95.9/4.1/0.0. The highest improvement was neck flexion/extension. Right shoulder was slightly negatively influenced by lower position during sitting, the ratio (%) between zones green/orange/red was changed from 72.8/18.6/8.6 to 72.0/19.0/9.0; the worst situation was in horizontal internal/external rotation. The similar situation was in left shoulder. Left hip achieved worse results, the ratio (%) between zones green/orange/red was changed from 89.7/10.1/0.2 to 72.8/21.0/6.2, which can be an effect of a short period using a new equipment by the employees. The worst situation was observed in left hip rotation. For right hip we observed better conditions than in left hip, the ratio (%) between zones green/orange/red was changed from 94.6/5.4/0.0 to 83.7/8.0/8.2.

Exoskeleton manufacturers inform about positive effects usually based on experiments in the laboratory environment. Their effect in the industrial environment needs to be verified from a long time frame. The advantage of a multisensor system is the collection of complex data at the same time, which simplifies the evaluation and effectiveness of measurements. Awareness about the influence of exoskeletons on individual parts of the body and the right choice of work activities may be beneficial for the design of healthy modern workplaces based on individual risk assessment.

Further research will focus on developing a methodology for risk assessment, considering the stress factor associated with the use of the exoskeleton (specific types) on the one hand and its impact on reducing WMSDs hazards. The influence of the exoskeleton understood as safety devices must be examined as an emerging risk (Constantino et al., 2021) or as emerging opportunities for improving the working environment and thus the health of employees resulting from the new trends of Industry 4.0.

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