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Framework of modular industrial assembly workstations in a collaborative environment

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Modern organizations aim to improve key economic parameters (productivity, effectiveness) in order to be competitive in global market. Furthermore, contemporary organizations strive to improve the health and safety of workers. One of the possible solutions to achieve that goal is to modernise production processes through the integration of lean principles and innovative technologies of Industry 4.0. However, in many monotonous and repetitive assembly operations, it is not possible to implement full digitalization. The focus of this research paper is to propose a modular human-robot workstation where the operator and collaborative robot share activities to improve workplace safety and worker's performance. The proposed modular assembly workstation, integrated with a poka-yoke system, is designed in accordance with the individual characteristics of the operator. Authors plan in future periods to conduct researches on this workstation in the field of neuroergonomics using an innovative electroencephalogram system (EEG) during assembly tasks with collaborative robot to prove that it will improve the physical, cognitive and organizational ergonomics and, at the same time, increase productivity and effectiveness.

Keywords: human–robot collaboration; Industry 4.0; lean principles; modular industrial assembly workstations; collaborative robot; poka-yoke system

1. Introduction

A large number of modern production organizations strive to meet the needs, requirements and expectations of customers through the production of quality products, with low costs and minimize time to market. On the other hand, they aim to improve the safety and health of their employees. The main goal of lean production system is to ensure a continuous flow of the process while shortening the time between ordering and delivery of products and eliminating all forms of waste (Shah and Ward 2003).

The Fourth Industrial Revolution (Industry 4.0) implies complete digitalization of production processes and the focus is on the increasing the efficiency and optimization of production processes through their automation using advanced technologies (3D printing, virtual and augmented reality, smart factories, smart logistics, ambient intelligence, etc.) (Kim 2017). Furthermore, Industry 5.0 promotes and redesigns jobs to make it fully human-centered (Nahavandi 2019) and transformation from manual to cognitive work (Guerin et al. 2019). Industry 5.0 is focused on the intelligent production and synergy between operators and intelligent systems such as collaborative robots (cobots) in order to most effectively combine the intelligence, cognitive thinking and creativity of people with the technical characteristics of advanced technologies (ElFar et al. 2020; Lu 2017).

A special challenge is the improvement of prefabricated workstations where workers perform repetitive, tedious and physically demanding assembly activities. Moreover, a particular challenge is to improve the productivity and performance of workers who execute tedious, repetitive assembly tasks over a long period of time.

Workers performing activities on a non-ergonomic workstation are particularly exposed to muscle strain and fatigue (Kim et al. 2017; Sun et al. 2019). Hence, excessive stress, stretching and bending can cause the appearance of musculoskeletal disorders (MSDs).

The main contribution of this paper is reflected in the presentation of an innovative prefabricated workstation for collaborative activities between operators and robots, where neuroergonomics research will be conducted in the coming period. The main goal of applying ergonomic principles on prefabricated workstations is to improve the workplace and, generally, the working environment, in order to minimize the risks of injuries at work, and the health of workers. At the new workstation, the cobot and the operator share a common workspace and perform assembly activities together. The quality of the final product is achieved by means of a built-in poka-yoke device which allows to prevent errors in production processes.

The motivation for writing this paper can be found in the fact that it is necessary to redesign traditional prefabricated workstations in order to adapt them to the individual characteristics, abilities and limitations of the operator.

2. Literature Review

High frequency of repetition of tasks in combination with other risk factors such as awkward body positions lead to increased fatigue, decreased concentration and slowing down the production process. Adequately designed workspace allows workers to maintain good posture, to perform fewer movements with less effort. It is of great importance to design a prefabricated workstation where workers will be more satisfied and productive to perform activities (Nielsen et al. 2017).

According to Bergman et al. (2001), MSDs are one of the most common health problems and causes of operator incapacity. MSDs in working environments cause absenteeism, disability, increased replacement costs (Maakip, Keegel and Oakman 2017), reduced efficiency and productivity (Matos and Arezes 2015; Van Eerd et al. 2015).

In two scientific research papers, Brito and his associates stated that it is very important to take into account ergonomic aspects when designing a workstation (Brito et al. 2017a). In this way, productivity is increased, activity time is reduced and the health condition of workers is improved by reducing the risk of MSDs (Brito et al. 2017b).

Furthermore, ergonomic design of workplaces is one of the most important prerequisites for improving production processes and creating a more efficient, safer and more comfortable workplace (Cimino et al. 2009). Numerous studies analyzed the impact of workplace design and respect for lean and ergonomic principles on productivity level (Vieira et al. 2012; Al-Zuheri, Luong and Xing 2016). Also, certain authors pointed out the connection between ergonomic workplaces and lean production (Aqlan et al. 2014) and concluded that integrating lean and ergonomic principles, on one hand, can improve the safety and health of workers by eliminating non-ergonomic movements (Galante, Bordalo and Nobrega 2014), and, on the other hand, increase efficiency and reduce activity time (Yusuff 2016). Adaptation of the workplace to the requirements of the operator is presented in scientific research works by adapting to the physical characteristics of workers and their abilities and skills (Heilala and Voho 2001).

The application of ergonomic interventions could result in large savings and improve productivity, quality and health and safety of workers, as well as increase their satisfaction (Yeow 2003).

Improvement of prefabricated workstations can be achieved by applying Industry 4.0 technologies that enable the transformation of traditional industrial production processes such as cobots, cyber-physical systems, Internet of Things, big data, cloud computing, virtual reality, augmented reality, etc (Lee 2015; Henning and Kagermann 2013). Advanced application of smart innovative technologies contributes to the improvement of the working environment and performance of operators who perform monotonous and repetitive activities by improving safety and health of workers, providing greater autonomy to operators, enabling self-development, increasing flexibility and efficiency of production processes (Gorecky et al. 2014; Lasi et al. 2014).

Collaborative operation between operators and robots especially contributes to the improvement of prefabricated workstations by improving the safety and health of operators while increasing the performance of operators (Lorenzini et al. 2019). The introduction of collaborative robots when performing assembly tasks reduces the execution time of activities (Kinugawa et al. 2017).

Palomba et al. (2021) have shown that the collaborative workstation will improve working conditions. By applying the RULA method (Mcatamney and Corlett 2004), the authors concluded that fatigue was reduced for 50% for the left part of the body and 57% for the right part of the body compared with the manual workstation. Pearce et al. (2018) have shown that framework for collaborative cooperation of human and robot minimized task tact time and physical strain of human, reduces physical stress in some tasks. Gualtieri, Rauch and Vidoni (2021) suggested redesigning a collaborative workstation to improve the operators' physical ergonomics and concluded that this is how it came about increasing the level of productivity and improvement of workplace conditions.

Fasth-Berglund and Stahre (2013) investigated the occurrence of errors during assembly activities and proved that the application of the "pick to light" system, which is based on the poka-yoke system, reduces errors. Flashing lights on the storage containers for parts and components guide the operator through the assembly process and inform which parts and components to use at which time to prevent the risk of mistakes. Siddhartha (2014) showed that the application of poka yoke on assembly lines drastically reduces production costs, improves the quality of the final product and increases operator satisfaction.

Cognitive load negatively affects workers' attention, memory ability and reasoning ability (Rabby et al. 2019). Sweller, Van Merrienboer and Paas (1998) monitored mental load, performance, and stress levels as cognitive load indicators. Psychological factors can cause musculoskeletal disorders (Mehta 2016). Fasth-Berglund et al. (2016) measured cognitive load via the EEG signal. In some scientific research papers, the assessment of cognitive load was performed on the basis of subjective self-reporting of workers and measurement of psychophysiological parameters (Ustunel and Gunduz, 2017). The advantage of using EEG in relation to classical subjective methods of self-assessment of the operator is reflected in the provision of objective data on brain activity and cognitive load.

3. Design of the Proposed Assembly Workstation

Swift and Booker (2013) state as basic characteristics of manual assembly activities:

- Production rates vary from low to medium depending on the complexity of the product, the number and size of components
- Production time, i.e. product delivery, is quite long (in some situations this process takes days)
- Assembly activities are quite complex (depending on the size of the finished product being assembled)
- During the performance of these repetitive activities, fatigue and concentration occur, which has a negative impact on the health of workers (physical and mental)
- Operator errors occur especially if the product is complex, if the parts are

difficult to insert or if the insertion space is limited, if the installation activities are performed incorrectly

- The quality of the final product largely depends on the abilities and skills of the operators assembling the product.

Nevertheless, the recent shift to wellbeing, sustainability, and resilience under Industry 5.0 has prompted formal discussions that manufacturing should be human-centric, placing the wellbeing of industry workers at the center of manufacturing processes, instead of system-centric approach in which manufacturing is only driven by efficiency, quality improvement and cost reduction.

Hence, the authors concluded that a special challenge of contemporary industrial system is the improvement of prefabricated workstations where workers perform repetitive, tedious and physically demanding assembly activities.

In order to be able to solve all the problems faced by workers who perform assembly activities in traditional production systems, the authors proposed a modular assembly workstation. The basic goal is the improvement of health and safety of assembly workers and their satisfaction and performance. The design of the new workstation is in line with the basic principles of ergonomics, taking into account the fact that the workplace, work tasks, instruments and tools must be adapted to the needs and requirements of the operator.

All parts and components storage containers are arranged according to lean principles and taking into account the individual reach and field of view for each operator individually to reduce bending, stress and stretching of the body. The flexible layout of the container for storing components provides the ability to change the layout and organization of the work environment and adapt the material flow to the characteristics of the product being assembled.

The modular prefabricated workstation has been developed with respect to the fact that the zones of the handling area are different for each person. The specifics of the new workstation are reflected in the fact that each operator can adjust the storage containers for parts and components to their needs in order to avoid poor posture and non-ergonomic movements.

The modular structure of the proposed prefabricated workstation allows the adjustment and adaptation of existing standardized workstation modules and components to operator requirements. The reconfiguration of the workstation and its elements is reflected in the adaptation of the workstation to the requirements of the product itself, assembly activities and the needs of the operator. Tool devices within the modular system allow work activities to be performed by the operator when he needs them and to easily return to the disposal position when they are no longer needed or move to another part of the workspace. The tools that the operator most commonly use placed closest to the operator in accordance with lean principles. On the proposed modular workstation, the operator and the collaborative robot (cobot) create a hybrid workspace in which they jointly perform assembly activities.

Cobots are a special type of robot that are able to perform tasks in collaboration with workers in a common workspace in modern industrial environments (International Federation of Robotics 2019). The cobot is in continuous interaction with the operator and provides support during the execution of precise, physically demanding and complex daily activities (Gualtieri et al. 2019). Moreover, unlike conventional industrial robots (Akella et al. 1999), cobots are safe, flexible, and easy to program and, in comparison with industrial robots, are safer to work with workers as they adjust their activities and speed to the proximity and abilities of workers (Robla-Gómez et al. 2017).

In the proposed workstation, the cobot is aware of the human presence taking care of the safety and risk criteria. It can notice, understand, and feel not only the human being but also the goals and expectations of a human operator. Just like an apprentice, it learns how an individual performs a task. Once it has learned, the cobot executes the desired tasks as the human operators do. Therefore, the human experiences a different feeling of satisfaction while working alongside the cobot.

The proposed workstation for collaborative activities between operators and robots, as shown in Fig.1, is designed in accordance with international standards ISO procedures (EN-ISO 6385:2016 2016).

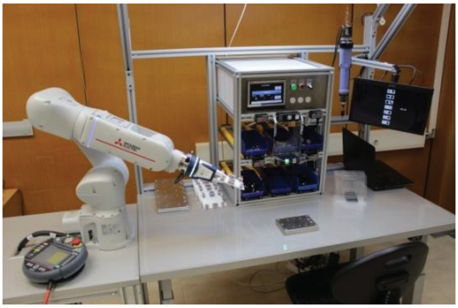

Fig. 1. Proposed modular assembly workstation

In the proposed human-robot interaction, operators perform activities that require dexterity, cognitive abilities, reasoning, decision-making and problem solving, and a collaborative robot performs precise and physically demanding activities. By applying cobots in production processes, significant advantages are achieved, increasing the productivity and performance of workers, improving the safety and well-being of workers, etc.

Besides, a built-in poka-yoke device guides the operator step by step through the assembly process through a sensor informing the operator about the occurrence of an error, the absence of a certain part and so on. The final inspection of the final product is performed by the operator. Table 1 shows the differences between the traditional workstation and the one proposed by authors.

Table 1. Traditional workstation vs. Modular workstation

Traditional Workstation	Modular Workstation
Not configurable	Self-Configurable
Fixed	Adaptive
Instructions on papers	Digital Instructions
Fixed height	Adjustable height
Fixed light	Adjustable light
Sitting workstation	Sitting and Standing position
No guided	Pick-by-light system

Finally, the combination of performing assembly activities in a sitting and standing position in the proposed assembly workstation provides an opportunity for operators to perform activities without feeling tired, exhausted and physically stressed.

4. Conclusion

Many organizations strive to improve the working conditions of operators performing assembly activities, their health and safety, and improve workers' satisfaction and performance (International Organization for Standardization 2009). The traditional workstation is fixed and not adapted to the individual anthropometric characteristics and abilities of the operator. Furthermore, it is not harmonized with ergonomic principles. Prolonged assembly activities in a non-ergonomic position causes the appearance of MSDs and other health problems. Also, the continuous effort of performing monotonous and repetitive activities causes a drop in attention and the appearance of fatigue after a certain time.

In order to improve the health condition and performance of the operator, a modular assembly workstation has been proposed as a hybrid production system, in which workers and a collaborative robot perform activities together. This mounting station complies with lean and ergonomic principles and is equipped with a poka-yoke device to prevent operator errors.

In the coming period, the authors plan to conduct various research. Indeed, neuroergonomics research will be conducted in order to monitor brain activity and determine when and how the concentration drops. In addition to the already mentioned neuroergonomics research, in the future, the authors plan to use modern advanced technologies of Industry 4.0 to collect real-time and process data on muscle activity of operators to determine when muscle fatigue occurs and the authors will propose solutions to reduce irregular movements and body position.

All of this research will be conducted without and with the introduction of a collaborative robot to monitor workers' health, effectiveness, and productivity. Also, the authors plan to use sensors to monitor the parameters of the working environment in which operators perform assembly activities (temperature, humidity, noise level, etc.). Some of the other parameters that will be monitored in the coming period are operator satisfaction, stress, well-being of workers in order to determine which factors have the greatest impact on productivity, and the effectiveness and efficiency of production processes.

Through the implementation of these researches, the authors expect that numerous benefits will be realized for operators performing assembly activities in real industrial environment:

- Reduction of musculoskeletal disorders and other health problems
- Prevention of injuries caused by ergonomically inadequate performance of activities
- Creation of a more pleasant and safer working environment
- Reduction of stress and exhaustion of workers
- Increase of the operator satisfaction
- Increase in productivity
- Improvement in product quality
- Reduction in absenteeism and costs related to sick leave and replacement of workers
- Improvement in the quality of life of workers and prolonging life and working life.

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