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Human-centered design for improving the workplace in the footwear sector

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Abstract

Especially in the footwear sector, the transition from the mass production to the mass customization increasingly requires Industry 4.0 solutions that do not reduce the human contribution to production processes but facilitate and value it to increase the job satisfaction. In this context, this paper proposes a method to (re)design the workplace according to a multiperspective ergonomic assessment. It efficaciously combines the analysis of physiological and environmental parameters by Internet-of-Things, the ergonomics risks identification by experts and the subjective evaluation of workers well-being. The method has been experimented in an Italian factory that produces customized shoes for the luxury market.

Keywords: Human-centered manufacturing; Ergonomics; Workplace; Artisanal production

1. Introduction

Despite the strong technological component, the fourth industrial revolution will not replace human resources within the factories but will lead to a transformation from a task-based organization model to a human-centered one, promoting the development of personal skills and workers well-being [1]. Therefore, ergonomics and human factors continue to play a key role toward social sustainability also in the new manufacturing paradigm [2]. In industrial–organizational psychology, a poor person–environment fit, which refers to the congruence between individual characteristics and the organizational context, can generate work-related stress, dissatisfaction, musculoskeletal disorders (MSDs), etc. [3]. It can result in increased costs and decreased output values. A proper job design has to include multiple domains such as environment, cognitive, physical, and organizational and has to achieve two goals closely interconnected. The former is fulfilling the expectations in terms of company performance (i.e., productivity, operational efficiency, quality). The latter is satisfying the needs of workers within their interests, challenges and achievements. It should be based on the cornerstone that individuals have different needs and preferences in terms of lighting, temperature, shifts, tasks content and so on. This approach allows providing safe work performance and reducing unnecessary effort.

As highlighted by the lean philosophy, it is important that the workstation design focuses on operator concerns as well as task requirements, although this approach is not common to find in industrial workstations [4]. A lack of knowledge is observed in the design or adaption of production systems considering both the technological and the human-centric perspectives as well as performance maximization [5].

On the other hand, the methods and tools for evaluating ergonomics risks are much more widespread. However, the data collection for physical demand and ergonomic posture assessment often depends on the direct observation. Consequently, the results are based on subjective evaluation by experts (i.e. inter-rater differences exist between different observers) and the analysis of potential risks could be time-consuming to achieve high accuracy levels [6]. Few studies foresee the use of wearable technologies for biomechanical risk assessment (e.g., inertial measurement units, surface electromyography sensors) although the growing need of quantitative evaluations [7].

Similarly, subjective evaluation based on rating scale techniques (e.g., NASA-task load index scale, subjective workload assessment technique) and task/performance-based

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techniques (e.g., primary-task performance measures, secondary-task performance measures) for the assessment of cognitive load have a widespread use and application in manufacturing compared to physiological techniques [8]. The use of physiological parameters is often limited to specific sector (e.g., aviation [9]) or to the assessment of new paradigms of human machine interaction [10]. It is mainly due to its complexity and obtrusiveness. However, with advances in Internet-of-Things (IoT), their regular use in the near future seems possible. Mattsson et al. [11] showed how the operator's wellbeing can be assessed in real-time, and from an assembly system perspective, through the measurement of the electro-dermal activity (EDA). However, they highlight the difficulty to interpret these data since the EDA is connected to several activities (both cognitive and physical) and suggest combining physiological measures and self-assessment techniques.

In summary, the following limits emerged: focus limited to a specific ergonomics domain/risk; poor combination of different measuring methods and prevalence of studies for risk assessment rather than structured approaches oriented to the ergonomic workplace design.

For this aim, this paper proposes a method to (re)design the workplace according to a multiperspective ergonomic assessment. It efficaciously combines the analysis of physiological and environmental parameters by IoT, the ergonomics risks identification by experts and the subjective evaluation of workers wellbeing. Moreover, it aims to extend the application boundaries to sectors based on traditional artisan mode rather than to the most common assembly lines (e.g., automotive sector), which are most frequently studied in the literature. Indeed, a challenge of this work would be to integrate the historical peculiarities of traditional artisanal mode with an intelligent factory context. For this aim, the method has been experimented in the footwear sector, also considering the growing interest in sustainability by fashion industry [12]. In particular, the most "critical" workstations (i.e., handmade painting, assembly and quality control of leathers) of an Italian factory that produces shoes for the luxury market have been analyzed and redesigned.

2. Method

The research methodology aims to support the human-centered (re)design of workplaces. It focuses on the improvement of workers' wellbeing, by involving them in a multiperspective ergonomic assessment.

As shown in Figure 1, it firstly requires a factory assessment to characterize workers, workstations and tasks. Then, it provides for the collection of data related to multiple ergonomics domains such as psychophysical and environmental. At this point, all data have to be analyzed to extract significant information in order to identify the ergonomics risk factors. The higher priority risks are then inserted in the columns of a correlation matrix to match them with the most proper corrective actions stored in the database. Finally, a set of (re)design guidelines is defined.

In the following paragraphs each step is described in more detail.

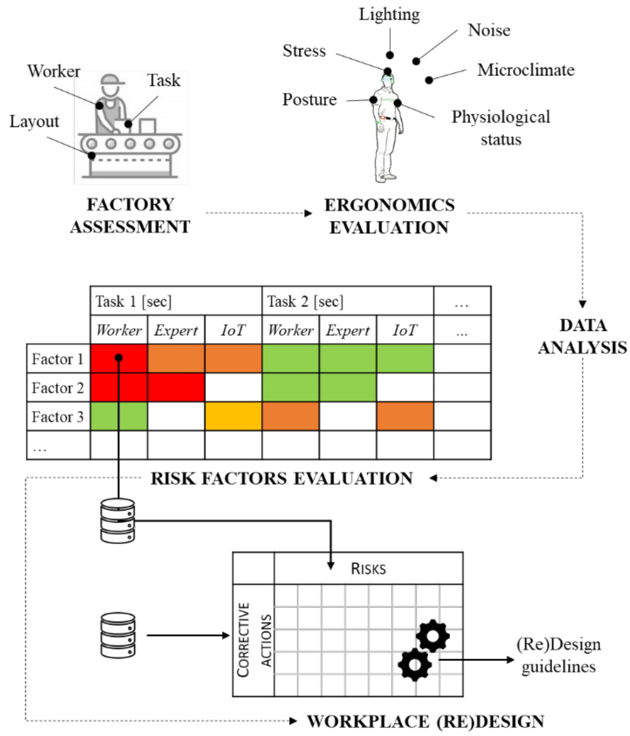

Fig. 1. Method.

2.1. Factory assessment

This step aims to create a data model of the factory environment. It considers all the workplace elements that could affect the risks the worker is exposed to. Data can be gathered from company DBs or by a direct acquisition. They refer to:

- Worker characteristics such as demographic variables, anthropometry, functional skills, knowledge, personal needs, etc. They allow personalizing the risk thresholds and design ad-hoc solutions;
- Workstation layout, which includes the physical arrangement of equipment, materials, etc. It mainly influences the working position and, as a consequence, the physical health of workers;
- Task characteristics such as type, duration, frequency, skills required, duties concerning the use of personal protective equipment (PPE), etc. They mainly affect the mental and physical human efforts and the hazards exposure.

2.2. Ergonomics evaluation

In this step, an ergonomics evaluation from a subjective and objective point of view is performed.

In the first case, experts and workers are involved. Experts are asked to perform a heuristic evaluation, which is based on the direct and video-based observation of users according to standardized ergonomics evaluation methods (e.g., RULA, OCRA, NIOSH). Workers are interviewed to consider their preferences and satisfaction about the workplace and to better interpret the analysis results.

In the second case, biometric and environmental parameters are collected automatically through the use of appropriate instruments or IoT devices. According to the analysis goal, monitoring can refer to different time slots (e.g., working cycle, shift, week) or be permanent.

2.3. Data analysis

Considering the heterogeneity of data and methods for their acquisition, it is necessary to define how they can be correlated. Firstly, the aspects to be evaluated should be defined. As shown in Figure 2, this paper focuses on physiological status, stress, posture, activity level, microclimate, air quality, light and noise. For each of them, the specific data to be considered and the analysis methodologies are described.

The physiological status considers the worker characteristics (age, height, weight) and vital parameters monitored by the BioHarness 3 (BH3). It is evaluated according to the proprietary algorithms of the OmniSense™ Analysis Software that calculate the following indicators: physiological intensity, mechanical intensity and ROG (Red-Orange-Green) status. They are based on heart rate, respiration rate, peak acceleration and activity. The three axial accelerometer values measured by BH3 are combined by the software to give a single acceleration magnitude in g. It allows defining the intensity activity level as follows:

- Light, VMU < 0,2 g;
- Moderate, 0,2 g ≤ VMU < 0,8 g;
- Vigorous, VMU ≥ 0,8 g.

Stress conditions are detected by analyzing the heart rate variability (HRV) and EDA, also known as galvanic skin response (GSR). The former is calculated by the abovementioned software. The latter, which is the change of electrical properties of skin, is measured by the Empatica E4 wristband. In this case, the skin conductance response is considered, which represents the faster and event related part of the EDA signal (phasic part).

For the postural assessment, the RULA (rapid upper limb assessment) technique [13] is used. It allows evaluating the exposure of individual workers to ergonomic risk factors associated with upper extremity MSDs. It is carried out by checklist during the heuristic evaluation. Experts are also supported by objective data (back flexion) measured by the chest band. Moreover, workers are asked to judge the posture they assume during the work shift.

The following environmental parameters are measured by the four sensors of Foobot: PM2.5, VOCs, temperature, and humidity. To determine the temperature that guarantees the workers' thermal comfort, according to their clothing and activity, the Fanger method [14] is used. The air quality is evaluated thanks to the global pollution index (GPI), which is a weighted compound of the different pollutants measured by Foobot. The Foobot application classify the GPI on four levels, from great (0-25) to poor (75-100).

A colorimeter is used to measure the color temperature and lux. According to the UNI EN 12464-1 [15] and CIE 1931 color space chromaticity diagram [16], the following three factors are evaluated: average maintained illuminance ($\bar{E}m$); the color rendering index (CIE R_a) and the illuminance uniformity (Uo). The light sources position is also considered.

The noise exposure is evaluated by a sound level meter and according to the limits about the Daily Personal Noise Exposure Level ($L_{EP,d}$) established by the Directive 2003/10/EC [17].

Workers are interviewed about their comfort in terms of microclimate, air quality, light and noise.

To evaluate the risk related to air quality, light and noise also the task performed is considered. Indeed, the task duration or the use of PPE influence the risks exposure.

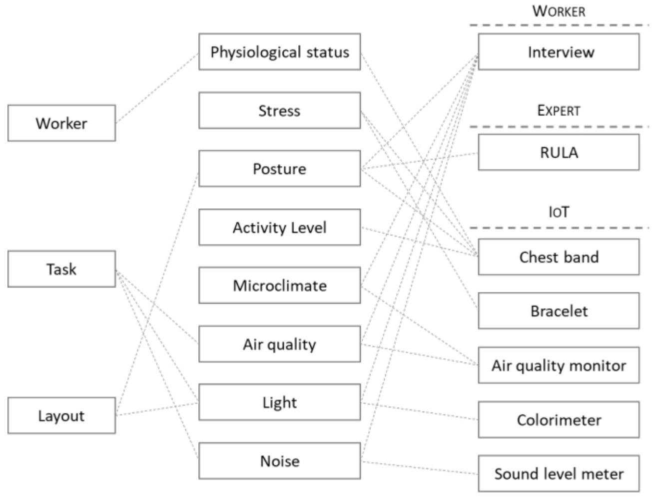

Fig. 2. Data correlation.

2.4. Risk factors evaluation

As shown in Table 1, for each risk factor, a set of thresholds are defined (some refer to the context of the case study). To be compliant with data provided by RULA and GPI, four levels of risk are defined: no risk (L1-Green), low (L2-Yellow), medium (L3-Orange) and high (L4-Red). Accordingly, a 1–7 points Likert scale is chosen to assign a value to each interview judgements (1 = strongly disagree, 7 = strongly agree). For the dichotomous thresholds (i.e., compliance or not with a regulatory limit) such as T, H, $\bar{E}m$, R_a and Uo, intermediate levels were defined by authors according to the time the threshold is exceeded during the shift.

Table 1. Thresholds of risk factors parameters.

Parameter	L1	L2	L3	L4
ROG	1	-	2	3
RULA	1-2	3-4	5-6	>6
T [°C]	20±3	≠ (17, 23)*	≠ (17, 23)**	≠ (17, 23)***
H	< 60%	≥ 60%*	≥ 60%**	≥ 60%***
GPI	0-25	25-50	50-75	75-100
$\bar{E}m$ [lx]	≥ 500	< 500*	< 500**	< 500***
R_a	≥ 80	< 80*	< 80**	< 80***
Uo	≥ 0,60	< 0,60*	< 0,60**	< 0,60***
$L_{EP,d}$	≤ 80 dB	80<dB≤85	85<dB≤87	> 87 dB
Interview judgements	7	5-6	3-4	1-2

*sporadic; ** ≥ 50% of the time; *** ≥ 90% of the time

The HRV is measured by the BH3 using the standard deviation of the normal to normal intervals (SDNN) and it is evaluated by the software according to a set of four-levels thresholds based on the age of the user. However, both the HRV and EDA are considered in comparative rather than absolute terms.

2.5. Workplace (re)design

The last phase is the decision-making in which for each risk identified in the previous step a series of corrective actions capable of eliminating or mitigating it are identified. They may concern (i) advanced components, tools and ergonomic solutions that support the operations execution; (ii) the ergonomic design of products, tasks and workstations; (iii) measures to ensure the safety and health of the working environment; (iv) organizational actions and (v) training initiatives. The corrective actions are inserted in the correlation matrix according to their ability to manage the emerged risks [18]. The (re)design guidelines are defined by selecting the minimum number of actions that allows mitigating all the selected risks.

3. Case study

The method was experimented in an Italian company that produces classic and luxury shoes, especially for men. Handmade workmanship is one of the core elements of distinction from its competitors that allows the distinctive features of the pure Made in Italy remaining unchanged through time. The company's will to monitor and improve the working conditions of its artisans is based on this pillar.

In particular, six operators of the department of made-to-measure shoes were involved. In this paper the results of the two ones working on shoe assembly and sewing are presented. The outcome of their work is a one-of-a-kind shoe, personalized in every single detail and fruit of the human manual ability.

The two operators, whose characteristics are shown in Table 2, were asked to wear the chest band BH3 and Empatica E4 wristband and were monitored for one shift. At the end, they were interviewed about the perceived wellbeing.

Table 2. Operators characteristics.

	Operator 1 (OP1)	Operator 2 (OP2)
Gender	M	M
Age	31	28
Height [cm]	175	170
BMI [kg/m2]	23.51	26.99
Workstation	Shoe manual assembly	Hand sewing
Shift	8am-12pm / 2pm-6:15pm	8am-12pm / 2pm-6:15pm
Break	9am-9:15am	9am-9:15am

3.1. Shoe manual assembly workstation

Assembling constitutes the core component of the shoemaking process. It consists of a series of strictly manual operations ranging from the leather stretching and adjusting over the last, to the application of the tip and a second layer of leather. In addition, operations of gluing, stapling and hammering are carried out in order to obtain a perfect adhesion to the last. The characteristics of the shoe manual assembly workstation are reported in Figure 3.

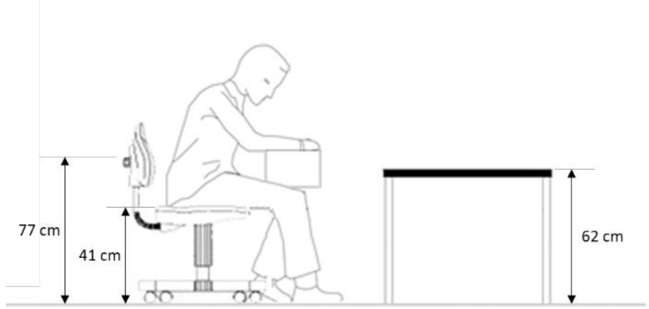

Fig. 3. Characterization of the shoe manual assembly workstation.

In Table 3, the results of the assessment related to the OP1 are summarized. The RULA score highlights a medium risk that mainly derives from the arm, wrist and neck posture.

As far as the environment is concerned, some parameters related to microclimate, air quality and lighting show high risks. In particular, the temperature was higher than that which guarantees a thermal comfort for the whole day. It is worth to specify that the measurements were carried out on a particularly hot day in July.

Air quality was acceptable for most of the shift, with the exception of the time in which the OP1 made a prolonged use of the milling machine. Although the workstation was sufficiently illuminated, a proper illuminance uniformity was not guaranteed.

Table 3. Ergonomics evaluation of the manual assembly workstation.

Risk factor	L1	L2	L3	L4	Interview
Physiological status	ROG	-			-
Posture			RULA		L3
Microclimate	H			T	L3
Air quality				GPI	L2
Light	$\bar{E}m$ - R_a		Uo		L2
Noise	$L_{EP,d}$				L1

From a physiological point of view, no critical issues were detected. The operators performed a light-intensity activity for most of the time, not requiring a significant effort. The greater energy expenditure was required by fixing the shoe on the last.

HRV resulted in the high normal range and the physiological intensity, which measures a person's cardiovascular output, was lower than 3 (where a score of 0 is a resting level whereas a score of 10 is equivalent to the individual working at their maximal effort).

The interview judgements confirm the objective measures. Indeed, the main discrepancies can be justified as follows:

- GPI is due to the fact that the milling activity last few minutes respect to the entire shift;
- The illuminance uniformity is more difficult to perceive in comparison of illuminance level.

3.2. Hand sewing workstation

The work of the operator of the hand sewing workstation consists of two main tasks:
1. Piercing of the leather pieces;
2. Sewing of the pieces composing the upper together.

During these operations the leather is temporarily fixed on a semi-soft support and alternately moved and fixed again changing its orientation with respect to the work surface, until all the phases have been completed. Then, the leather is permanently removed and destined for later processing.

The characteristics of the hand sewing workstation are reported in Figure 4.

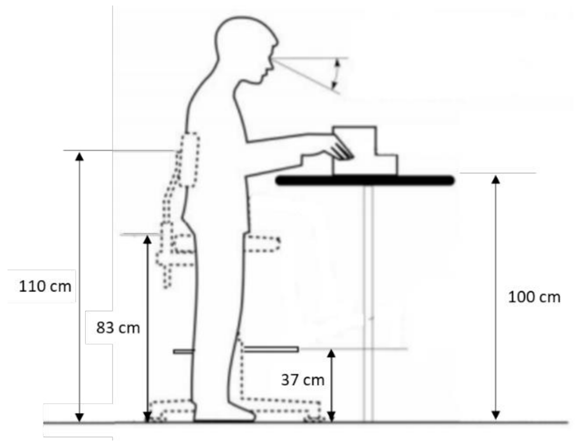

Fig. 4. Characterization of the hand sewing workstation.

In Table 4, the results of the assessment related to the OP2 are summarized. In particular, three potential risks were observed. The most critical are related to microclimate and lighting. In the first case, the temperature exceeded the threshold for the whole shift. In the second case, the average maintained illuminance was absolutely insufficient to guarantee an adequate visual comfort.

A medium risk is shown by the RULA score that derives exclusively from the posture of the neck.

Table 4. Ergonomics evaluation of the hand sewing workstation.

Risk factor	L1	L2	L3	L4	Interview
Physiological status	ROG	-			-
Posture			RULA		L2
Microclimate	H			T	L1
Air quality	GPI				L2
Light	R_a - Uo			Ēm	L4
Noise	$L_{EP,d}$				L1

The OP2 performed a sedentary activity for the entire shift as confirmed by the physiological intensity that was always lower than 2. The HRV and EDA signals showed some potential indicators of stress after the break in the morning and at the beginning of the afternoon shift (after lunch).

In this case, the worker perception is quite in line with the results of the expert based evaluation and the objective analysis, with the exception of the microclimate.

3.3. Workstations redesign

First of all, it is worth to point out that any intervention had been undertaken should not have compromised the quality of the operations carried out by the operators. Accordingly, the L4 risks (red) and L3 risks (orange) were inserted in the correlation matrix and the company manager was supported in the selection of the most appropriate corrective actions to follow as guidelines for the workstations redesign (Figure 5).

ACTION \ RISK		Lighting	Agents exposure	Microclimate	Awkward posture: neck	Awkward posture: back	Awkward posture: upper limbs	Workstation layout	Lack of tools supporting healthy body posture
DESIGN	Workstation layout allowing operators work within the strike zone/golden zone				1,2	1	1		
	Adjustable work surface				1,2	1			
	Provide ergonomic workstation accessories to increase workers' comfort						1		1,2
	Ensure a proper sitting posture				1,2	1			
	Ensure an appropriate lighting on the work surface	1,2							
WORKPLACE	Ensure thermal comfort			1,2					
	Ensure adequate lighting	1,2							
	Introduce suction systems and air recirculation systems		1						
	Provide appropriate PPE		1						
TRAINING	Provide best-practices to better execute tasks				1,2	1	1		

1: manual assembly workstation (OP1)
2: hand sewing workstation (OP2)

Fig. 5. Correlation matrix between risks and corrective actions

In particular, the same lighting system of the assembly workstation has been installed in the hand sewing workstation optimizing the height according to the operator seat. It allowed ensuring an adequate illuminance. The workstation arrangement within the area have been revised in order to improve the thermal comfort (i.e., proximity to the air vents) and ensure a proper illuminance uniformity. A dedicated suction system to the milling machine has been installed as well as providing adequate PPE.

An ergonomic chair and an adjustable footrest have been provided to the OP1 to avoid an excessive inclination of the back. An ergonomic stool and an adjustable desk have been provided to the OP2 to improve the neck posture.

4. Results

In Table 5 the main results of the redesign activities are summarized. All the operators were monitored again for one shift. As shown, all L4 risks were eliminated (lighting and air quality) or reduced (microclimate).

For both operators, the RULA score was reduced from L3 to L2 by improving the neck and back posture. A positive feedback about the corrective actions implemented was given by the two operators, especially for lighting and physical ergonomic of the workstation.

Table 5. Risks mitigation after the workstations redesign.

Workstation	L1	L2	L3	L4
WS1 - Before	6	2	4	2
WS1 - After	10	3	1	0
WS2 - Before	8	2	1	3
WS2 - After	9	4	1	0

Overall, the experimentation was evaluated through an ad hoc questionnaire administered to the workers. According 7-point Likert scale from 1 (strongly disagree) to 7 (strongly agree), it aimed to investigate the following aspects:

- Devices' intrusiveness in terms of physical and emotional discomfort (i.e., obstacle, invasiveness, intrusiveness);
- Influence of monitoring devices on the usual way of carrying out the work (i.e., pressure, motivation, focus);
- Awareness about ergonomic risks and the perceived usefulness of the analysis (i.e., usefulness, awareness, proactivity, importance).

Figure 6 reports the opinions of the all six operators involved. In general, the trial was evaluated positively, increasing their awareness about ergonomics risks. The influence in the way of performing the work resulted absolutely subjective. The use of wearable devices generated conflicting opinions. In particular, wearing the glasses causes discomfort to some operators (not reported in this paper) sometimes hindering their work (quality control).

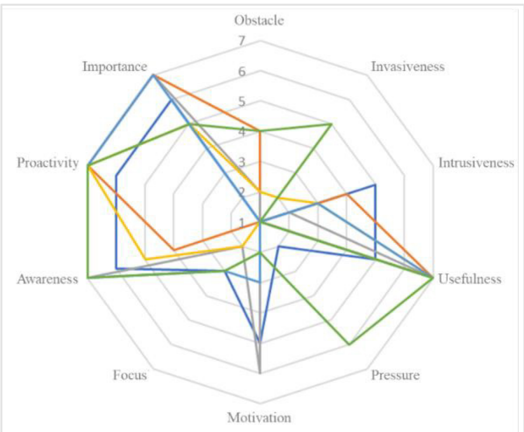

Fig. 6. Workers opinions about the experimentation.

5. Conclusions

The paper proposes a multiperspective ergonomic assessment method to support the workplace (re)design according to a human-centered design approach. The effective combination of physiological parameters measurement, expert based methods and self-report techniques allows performing a holistic assessment of workers wellbeing and identifying potential ergonomics risks. The method was successfully experimented in the footwear sector, where a strong artisan component prevails. Without impacting the execution of value-added work, the workstations have been effectively redesigned, mitigating the highest ergonomic risks.

Future applications of the method will concern the human-robot collaboration that includes the workers' acceptance and trust toward their coworker, new stressors, different perception of workload, new opportunities to improve ergonomics aspects as well as safety issues. A dedicated tool will be developed to connect the measuring methods to each other. New algorithms will be defined to detect significant patterns between the risk factors detected by subjective and objective evaluations.

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