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Digital Technologies to Redesign Automatic Machines with a Human-Centric Approach: Application in Industry

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Abstract. Human factors integration is definitely a transdisciplinary and urgent matter in modern factories. Despite the great surge in factory automation in recent years, human-machine interaction is still a crucial aspect and companies need to take care of the workers' wellbeing and performance to enhance the overall system quality and productivity. Nevertheless, ergonomics is poorly considered during the design of complex industrial systems, such as automatic machinery, especially for the lack of practical methodologies and guidelines to promote human factors from the early stages of design or redesign. To overcome this issue, this work proposes a transdisciplinary approach to redesign automatic machinery in compliance with factory ergonomics, using a combination of digital technologies (e.g., digital human simulation, human physiological data monitoring). The paper defines a structure method and related tools to apply a human-centric approach to industrial cases and their validation of a real case, concerning the redesign of a packaging automatic machine. Results show how the proposed approach is useful to detect possible ergonomic issues at the shop floor, identifying in advance risky situations for the operators during operating or maintenance tasks, and leading to an optimized machine able to enhance the workers' wellbeing and factory productivity at the same time.

Keywords. human-centered design, ergonomics, human factors integration, digital human simulation, human monitoring

Introduction

The Industry 4.0 (I4.0) concept [1] brought along a real revolution as far as machinery and workspaces, introducing a set of enabling technologies [2] able to improve at the same time productivity and flexibility of the modern factories. In this scenario, characterized by a high level of automation, human beings are still at the core of industrial processes, due to their inner capacity to adapt to new operations and their high level of flexibility in problem solving [3]. So, it is crucial to support operators during the work shift starting from the design of the modern factories in compliance with factory ergonomics, according to the Operator 4.0 concept theorized by Romero et al. [4].

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Generally, ergonomics principles are scarcely applied during the design of complex systems, such as automatic machines, mainly due to the difficulty to link human factors to process performance. Despite this common belief, Neumman and Dul [5] demonstrated a direct correlation between the workers' wellbeing and the system performance, paving the way for a different approach according to Human-Centered Design (HCD) [6]. The main objective is to reduce the operators' overall physical and mental workload, minimizing the risk of exposing workers to ergonomic risks that adversely affect their performance and wellbeing. To achieve this goal, human factors need to be considered from the early design stages to predict static and awkward postures, repetitiveness of tasks, handling of heavy loads, and reachability and visibility issues.

In order to support the human factors integration in modern factories, this paper proposes a transdisciplinary methodology that merges different branches of knowledge to include people in the design of industrial machinery, bridging the gap between technical and social sciences [7]. The aim is to use digital tools (i.e., digital simulation and motion capture) and human monitoring tools to anticipate the workers' tasks on the machine and optimize both the machine design (e.g., layout, part positioning, disassembly sequence) and the processes (e.g., maintenance and routine operations). Moreover, this work describes the practical application of this methodology to an industrial case concerning the redesign of an automatic machine for packaging.

1. Research background

As pillars of I4.0, digitalization allows predicting the workers' behavior and optimizing the industrial process, preventing work-related musculoskeletal disorder (WRMSD) and ensuring the optimal performance of the operational sequence [8]. In particular, digital human simulation (DHS) uses virtual mannequins acting into a virtual working environment to identify the main ergonomic problems, according to different ergonomic assessment methods like Rapid Upper Limb Analysis (RULA), Ovako Working posture Analysis System (OWAS) or NIOSH. Despite this advantage, DHS has some limitations: simulation is based on task division in subtasks and analysis for each static posture, providing an evaluation of the static task sequence and barely considering the dynamic aspects of human-system interaction [9]. Moreover, the simulation preparation phase is time-consuming, strongly depending on the analyst's experience, and can suffer from unnaturalness in posture prediction [10]. To overcome these limitations, motion capture systems could be used to analyze movements and behaviours of real users through dedicated systems, allowing a real time postural analysis on a continuous flow of actions, closer to real activities and it could be used also on-field [11]. The combination of DHS and motion capture can have positive effects and could enhance the industrial ergonomics [12].

Beside human simulations, a growing importance is given to the analysis of human physiological data in order to monitor the user experience (UX) of operators [13], enhancing the workers' wellbeing, safety and satisfaction and contemporarily improving the overall factory performance. Wearable devices, such as smartwatch or smartbands, can be used to collect the heart activity or the stress condition of the operators in order to understand their health and prevent harmful conditions. The proposed methodology try to exploit the benefits of DHS, motion capture and human monitoring by combining them into a framework to support the design process of automatic machines.

2. Methodology

The purpose of the proposed methodology is to support engineers and designers during the design phase of complex systems like automatic machines, using a human-centric perspective. The application of this methodology promotes the consideration of ergonomic principles at the early stage of system design to prevent design errors and to promote the workers' wellbeing during maintenance and routine operations on automatic machines.
Such a methodology is applied from the analysis of real users acting on the current machine, to collect useful data about the current human-machine interaction including working sequence and workers' workload. After that, digital simulation is used to carry out the ergonomic assessment using virtual mannequins and to redesign the machine to optimize the workload.
In order to achieve this goal, the methodology involves the use of the following digital tools:

- Motion capture: to capture the movements of real users and to understand their effort, a set of light and low-cost wearable trackers is used (i.e., HTC Vive Trackers 3.0). In this specific case, the operator wears the trackers according to a predefined configuration (i.e., two trackers on the arms, two on the legs, one on the torso and one on the waist). Moreover, a dedicated plugin for Unity3D (i.e., XRErgo®) is used to allow the real-time evaluation of the users' postures within a virtual simulation, as a digital twin of the operator to assess the postural risk. A specific software (i.e., Steam VR) collects the real time positions from Vive Trackers and streams it in XRErgo in order to perform the ergonomic analysis. An external camera (i.e., Sony RX 100V) is used to collect the external scene;
- Human monitoring: the study adopts an eye-tracking glasses (i.e., Tobii Pro Glasses 2) and a sensorized wristband (i.e., Empatica E4) to collect respectively the real users' eye movements and a set of human physiological data. In particular, Empatica is equipped with a photoplethysmogram (PPG) sensor that measures the Blood Volume Pulse (BVP), from which the heart rate (HR) and inter beat interval (IBI) can be extracted, and a skin conductance sensor, able to monitor the electrodermal activity (EDA). A specific software (i.e., E4 realtime) is used for the real time data streaming from the wrist-band to a smartphone or a tablet for calibration and data recording;
- Digital human simulation: the study uses a digital human modeling tool (i.e., Siemens Tecnomatix® Jack) to simulate the human-machine interaction and the operators' activities by virtual mannequins. Physical effort on human operators can be analyzed with realistic and scalable human models and different ergonomics indexes.

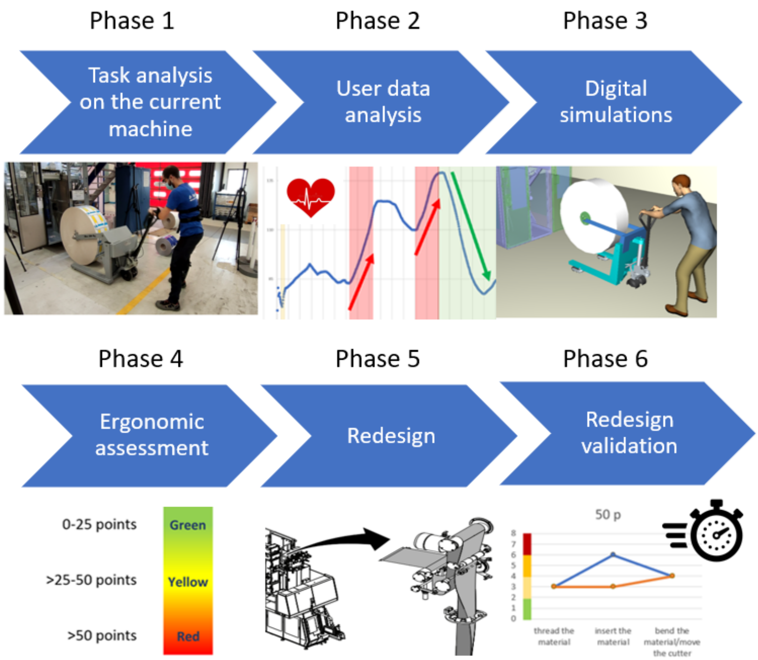

Figure 1. Phases of the proposed methodology.

The proposed methodology to redesign automatic machines requires several phases (Figure 1), listed below:

1. Task analysis on the current machine: in this phase, users with different levels of expertise are involved and asked to perform a certain task on the current machine. During task performance, the motion capture system tracks the posture of the operator while the wristband collects data about HR and EDA. Moreover, the eye-tracking glasses record the user's point of view and track the variation of his pupils diameter (PD) and eye movements. After data collection, users are asked to judge the level of perceived comfort during the task for body joint angles by questionnaire;
2. User data analysis: the previous collected data about HR, EDA and PD are post-processed in order to highlight any issues during the execution of certain tasks. To do this, the mentioned parameters are plotted in a graph in time-domain to detect the most critical activities for operators in terms of physical fatigue and stress;
3. Digital simulations: the analyzed sub-tasks are replicated in the digital human modeling software using virtual mannequins. The 3d model of the current machine is imported into the software and the postures assumed by the operators during the tasks are reproduced statically, considering different mannequins percentiles and populations;
4. Ergonomic assessment: the postural data files of the virtual mannequins created in the previous phase are exported from the DHS software into a dedicated excel file and evaluated through internationally-recognized ergonomic indices to

assess the risk to develop WRMSD. In particular, EAWS (European Assembly Work-Sheet) and RULA (Rapid Upper Limb Assessment) methods are adopted. This phase is able to detect the main postural issues during the task execution to be fixed in the next version of the machine;

5. Redesign: considering the ergonomic issues detected in the previous phases, engineers and designers can apply design changes in the machine layout, components' position, task sequence, or reciprocal position between the operator and the machine, in order to fit ergonomic principles;
6. Redesign validation: a new ergonomic assessment is required in order to validate the proposed changes. This phase continues until all the ergonomic targets are satisfied.

3. The industrial use case

The industrial case has been developed in collaboration with a global leader in the design and manufacturing of a wide range of automatic machines for food packaging. In particular, this study concerns the redesign of automatic machines for the creation of packaging for beverages, with the goal of optimizing the operators' workload during maintenance procedures and routine tasks. As a matter of fact, the analyzed machine creates a sort of "brick" using a special material mostly composed of paper, polyethylene plastic and aluminum: the latter, thanks to a very thin internal layer, protects the contents from both oxygen and light. For sake of brevity, this paper considers the application of the methodology to only one task, the most frequent during the use of the machine: refill of the packaging material. This operation is usually performed by the operator every 30 minutes, when the machine is at the maximum speed and requires about 10 minutes for an expert operator to complete the task. To simplify, the operator has to replace the finished reel of packaging material with a new one inside the machine. In the next paragraphs, the main steps of the proposed methodology applied to the presented industrial case are shown.

3.1 Task analysis on the current machine

Task analysis was executed involving three operators as employees of the company, with different levels of expertise (1, 3 and more than 10 years of experience). User participation was voluntary and no reward was given. All participants signed an informed consent before the analysis. All of them presented normal vision and did not need corrective lenses, and none of the participants had heart conditions. The refill of the packaging material was performed one user at a time in the company machines test area. Firstly, a brief pre-test questionnaire had been defined and administered to the user to collect demographic information and to understand the familiarity with the considered operation. They was asked to wear the HTC Vive Trackers (n.6), Empatica E4 and Tobii Glasses 2. After a short calibration of motion capture and eye-tracking systems, three-minutes of signal recording from the wearable sensors in resting condition (upright, being still) were established at the beginning of the task execution to analyze the baseline of each physiological parameter. Then, the user performed the task while the video camera and motion capture system recorded his movements. The task sequence for the packaging material refill, as analyzed by user task analysis, is described in Table 1.

Table 1. List of subtasks for packaging material refill operation.

No.	Subtasks	No.	Subtasks
1	Open machine right door	15	Down movement
2	Reach reel spindle	16	Align the load
3	Lift reel spindle	17	Release the reel of packaging material
4	Remove spindle	18	Remove the trolley
5	Reach the reel of packaging material	19	Approach the machine
6	Grab the reel of packaging material	20	Unroll the packaging material
7	Move the reel of packaging material	21	Push "material locking" button
8	Align reel spindle	22	Move cutter to the right
9	Insert reel spindle	23	Packaging material insertion
10	Reach the trolley	24	Bend superior edge
11	Grab the trolley	25	Cut with cutter
12	Aligh the trolley	26	Close the machine right door
13	Lift the reel of packaging material	27	Push "reset" button
14	Up movement	-	-

3.2 User data analysis

In this phase, the users' physiological data such as HR, EDA and PD were graphed in time-domain to understand which subtask is more critical for the participants. For each user, data analysis was carried out comparing the values collected for each parameter in rest condition (baseline) and during the sub-task execution, highlighting the most significant trends in parameter variation.

3.3 Digital simulation

The process was digitally replicated using Tecnomatix Jack, importing virtual mannequins replicating the real users' movements for each sub-tasks into the virtual environment. The current machine is virtually represented using the 3D model of the automatic machine provided by the company. The main postures assumed by the operator during each sub-task execution, according to Table 1, were simulated and compared with the motion capture data, to evaluate the operators' physical effort (Figure 2). Digital simulation was performed on three different human percentiles from different populations databases: 5th Thailand, 50th German and 95th Dutch. The height of the machine was considered at its minimum (i.e., 155 mm from the group).

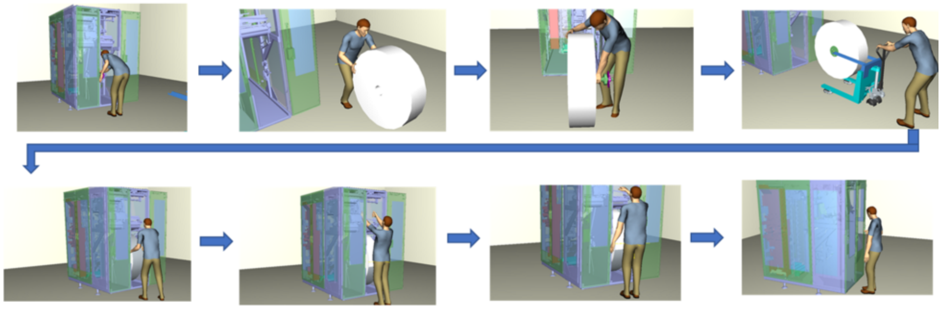

Figure 2. Digital human simulation of the refill packaging material operation.

3.4 Ergonomic assessment

The ergonomic assessment was performed using different ergonomic indexes, EAWS and RULA. EAWS is an holistic ergonomic method for measuring the workload activity during an entire work shift, frequently adopted for assembly workstation; it considers body postures, action forces, manual materials handling, and upper limbs during all the task duration [14]. In this case, the EAWS score was calculated in a semi-automated way, extracting postures directly from the digital simulations and importing them into a previously developed EAWS-Jack excel worksheet [15]. Similarly, the RULA ergonomic assessment method considers biomechanical and postural load requirements of job tasks/demands on the neck, trunk and upper extremities. In this case, the RULA score was directly generated by the XRErgo software, exploiting the motion capture system. In general, the EAWS allows evaluating the physical effort during the entire process, providing a score from 0 to up to 50, increasing with the degree of risk. On the contrary, RULA focuses mainly on postural ergonomics, giving feedback with a 1 to 7 score.

3.5 Redesign

The redesign objective was to reduce the EAWS global score of the task and at the same time, decrease the RULA score of the most critical tasks. Moreover, the main criticalities encountered during the ergonomic assessment and highlighted by the physiological data post-processing have to be corrected, in order to improve the overall workers' experience. In this case, the layout of the machine was changed, starting from greater machine dimensions to improve the accessibility during the maintenance operations. In addition, the rollers system used for the unrolling of the packaging material was symplified and lowered in order to facilitate reachability during the packaging material insertion.

3.6 Redesign validation

Steps no. 3.3 and no. 3.4 were repeated in order to create a new digital simulation on the redesigned machine and, consequently, a new ergonomic assessment was carried out as previously explained. Then, the EAWS and RULA scores were compared in order to assess the goodness of the redesign stage.

4. Results

Results about the physiological data post-processing are reported in Figure 3; for sake of brevity, only data on one operator are reported, but trends are similar for all the operators. Regarding HR, it showed a significant increase during the most physical sub-tasks, such as the reel lifting and the unwinding of the reel material, while it showed a decrease during the most mental tasks, such as the insertion of the packaging material. On the contrary, PD showed a decrease during the execution of the most physical subtasks, while the diameter increased when higher cognitive effort is required, index of an augmented mental workload, such as during the insertion of the packaging material into the gate. Differently from these two, the EDA graph did not highlight particular trends in any sub-task, so it was omitted in the figure.

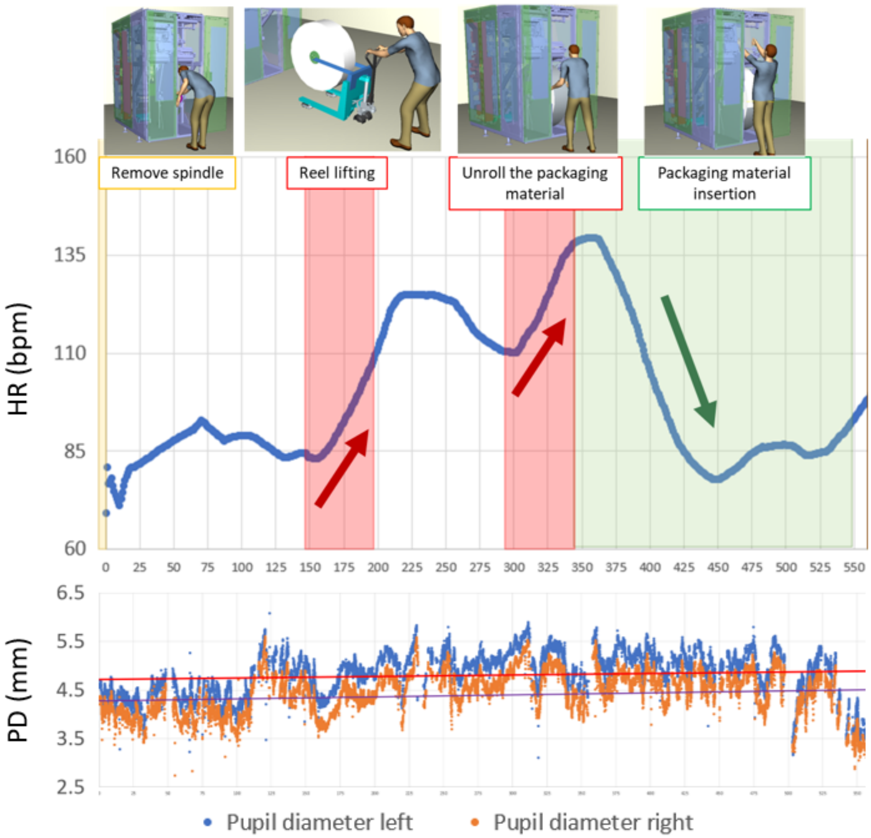

Figure 3. HR and PD graphs during the refill of packaging material task.

Considering the ergonomic evaluation, Table 2 shows the EAWS score obtained by the application of the digital human simulation tools for the three considered percentiles. In general, the scores indicate a higher risk to develop WRMSD due to the greater effort to move the heavy reel. The redesigned machines show a significant decrease in the EAWS general score, highlighting a sensible enhancement of the operators' conditions.

Moreover, the RULA score (Figure 4) is sensibly reduced in the main subtasks, especially for operators of 5th and 50th percentile. Focusing on the operators' performance (Table 3), the time to complete the tasks for the three considered operators are summed up for the original machine design and the redesign. As it was desirable, the time to complete the task in the new version is reduced, and the less expert operators have the major benefits in terms of time saved.

Table 2. EAWS scores for all the percentiles in the two machine versions.

Percentile	EAWS score AS-IS version	EAWS score TO-BE version	EAWS score decrease
5th	64.5	54.1	-10.4
50th	60.6	52.3	-8.3
95th	59.8	50.8	-9.0
Mean (Variance)	61.6 (6.3)	52.4 (2.7)	-9.2 (1.1)

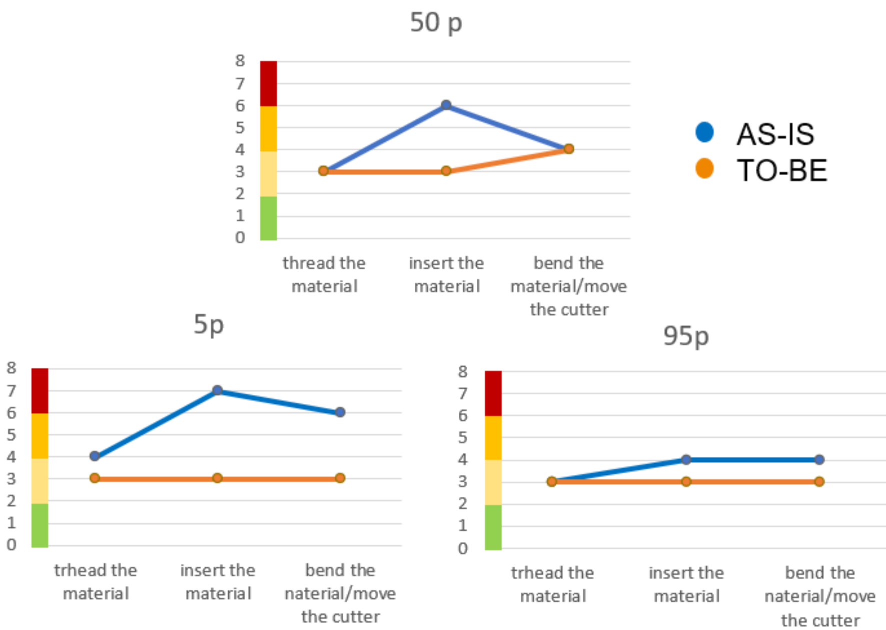

Figure 4. RULA scores for the main subtasks for 5th, 50th and 95th percentiles.

Table 3. Time to complete the tasks for all the operators in the two machine versions.

Operator no.	Expertise	Time to complete the task AS-IS version (min)	Time to complete the task TO-BE version (min)	Save of time (min)
1	>10 years	6:04	4:05	1:59
2	>3 years	8:30	7:06	1:24
3	>1 year	12:00	9:02	3:02

5. Conclusions

The paper investigated the application of digital tools and human-centric approach to effectively redesign automatic machines to benefit operators' ergonomics. In particular, the paper proposed a transdisciplinary methodology that merges different fields of knowledge and directly involves people from practice in order to promote a human-centric way of designing complex systems. It means an effective integration in the engineering world of the human social sphere, considering the well-being of the operators during the redesign process. Moreover, the outcome is an improved decision-making capacity of the companies that can develop machines in compliance with factory ergonomics. The application of the proposed methodology to a real industrial case demonstrated the benefits for the operators' wellbeing, reducing the risk of developing WRMSD, but also enhanced performance of the operators (shorter time and easier tasks). Moreover, the ergonomic evaluation carried out by internationally recognized indexes (EAWS and RULA) gives precise feedback about the main criticalities of the systems, such as reachability, visibility or postural disease. Regarding the main limitations of the study, the complexity of the technological set-up and its cost have to be counted for.

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