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The benefits of human-centred design in industrial practices: re-design of workstations in pipe industry

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Abstract

Sustainable Manufacturing (SM) traditionally focused on optimization of environmental and economic aspects, by neglecting the human performance. However, the industrial plant's costs, productivity and process quality highly depend on the individual human performance (e.g., comfort perceived, physical and mental workload, simplicity of actions, personal satisfaction) and how much hazardous positions and uncomfortable tasks finally cost to the company. The present paper defines a human-centred virtual simulation environment to optimize physical ergonomics in workstation design and demonstrates its benefits on an industrial case study in pipe industry. The proposed environment aims at overcoming traditional approaches, where analysis are carried out at the shop-floor when the plant is already created, by providing a virtual environment to easily test and verify different design solutions to optimize physical, cognitive and organizational ergonomics.

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Keywords: Human-Centred Design (HCD), Manufacturing Ergonomics, Digital Human Models (DHM), Virtual Reality, Workstation design.

1. Introduction

Sustainable manufacturing aims at creating sustainable manufacturing processes, reducing the impact of the three sustainability areas: environment, economy, and society [1]. While a lot of attention has been paid during the recent years to environmental impact reduction and cost optimization [2], the social dimension is still vague considered. However, the importance of the social impact on the modern processes has been recently pointed out by several

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sources all around the world. The fourth industrial revolution is starting to transform not only the modern companies, but also the way people interact with products and processes due to the change in product smartness as well as the work environments through 2025 and beyond [3]. This fact will have significant implications on the nature of product and process design, and will drive the so-called human-centred evolution in the design and usage of manufacturing sites and production systems [4]. However, real benefits can be achieved only when sustainability assessment is introduced during the early design stages, and sustainability becomes a design driver that serves to optimize the sustainability performance before product creation and process definition, to reduce production times, and to avoid late optimization loops [5]. In order to promote sustainability, different validation and verification assessment models are diffusing in industry. The interest of manufacturing companies to the human-related aspects optimization is arising for two main reasons: regulations and costs. On one hand companies have to care about workers' health and avoid work-related musculoskeletal disorder (MSD) as regulated by laws in different countries and sectors. On the other hand, the great economic impact of MSD connected to unnatural positions and dangerous actions executed by workers for both industry and society has been demonstrated in numerous cases. More specifically, bad workplace ergonomics has also extremely negative impact on company productivity, product quality, safety and production costs as analysed in different industrial sectors [6]. However, the actual practices are based on ex-post analyses to monitor the existing conditions by ad-hoc simulations created on monitoring the real processes. As a consequence, actions are usually taken after the design stage, when products and/or processes are already developed.

In this context, digital mock-ups are commonly used throughout the design phase, starting from the conceptual design phase to digital mock-ups validation in the advanced stages of the design process. Design tasks can be successfully reviewed by full-scale stereoscopic visualization within an immersive virtual environment [7]. These tools provide a virtual representation of workers in a simulated working environment and support the identification of ergonomic problems. However, such simulations have some limits in reliability, robustness and completeness of simulation. Indeed, the majority of tools use static scenes of single working postures and analyse only physical aspects without considering the cognitive aspects as well as the mental workload. However, actual tools difficultly allow the evaluation of both physical and cognitive ergonomic aspects, are not able to include the subjective impressions of workers, and do not consider to the workers' needs, skills, capabilities, and resilience (the so-called human factors).

The paper aims at demonstrating the benefits of a virtual simulation by the use of an immersive simulation environment adopting virtual reality (VR) technologies and mixed prototyping, merging real and virtual objects, to optimize physical ergonomics in workstation design. The study has been developed in collaboration with a leader company in energy industry for the optimization of the social sustainability of its workstations. The immersive virtual simulation was proved to support re-design actions by anticipating the human factors assessment during the design stage by involving real users, validating the plant layout, and improving the overall process quality.

2. The research background

Human factors have been recognized as a fundamental aspect in industrial engineering, so that ergonomics is always more often considered in industrial products and systems design. The analysis of human factors is focused on the analysis of the effectiveness and the efficiency with which activities and tasks are carried out, related to both physical and cognitive workloads [8]. As far as industrial operations, in different contexts it has been demonstrated that human factors highly affect the global efficiency of industrial processes [9][10]. Low attention to human factors brings to unnatural positions and dangerous actions executed by workers during their jobs, with consequent lower performances, higher production time, greater absence from work, and a general increase of Musculoskeletal Disorders (MSDs) with a consequence impact on national economies, in Europe as well as in other countries [11]. Such evidences are pushing companies to pay increasing attention to the evaluation of ergonomic performances based on different methods: from NIOSH equation [12] to the Ovako Working posture Analysis System (OWAS) [13], from the Occupational Repetitive Actions (OCRA) analysis [14] to the Rapid Upper Limb Analysis (RULA) [15], the Rapid Entire Body Assessment (REBA) [16] or Workplace Ergonomic Risk Assessment (WERA) [17]. In order to carry out proactive ergonomic assessment, digital simulation tools allow reproducing the human actions by digital human models (DHMs) and simulating the interaction with objects in a virtual environment. Different technologies are available: Siemens JACK [18] and Dassault Systèmes CATIA/DELMIA HUMAN [19] are the most widespread for industrial applications. Using these tools, the biomechanical attributes of specific postures, the visual scope and the reach envelope of users representing specific populations can be analyzed. However, digital simulations usually are not able to assure a robust estimation of the human workload since simulations are generally referred to discrete analysis on static positions, instead of a dynamic process simulation, they provide specific results for the analyzed condition, without any indication about corrective actions. Moreover, they mainly focus on static physical ergonomics, without a real interaction simulation. Virtual reality (VR) simulation offers immersive environment where the users' can interact with the virtual prototypes to validate workplaces' layout and interaction feature on digital mock-ups [20][21]. However, their application for companies is still limited due to the lack of results about cost-benefits analysis.

3. The research approach

3.1. The simulation approach

The methodology used is based on task analysis and digital simulation. Task analysis allowed focusing on the activities to be simulated by subdividing them into a set of sub-tasks, identifying the simulation fixed and variable parameters and external conditions, and highlighting the human-system interactions. Simulations were carried out in two different modalities. The first simulation is executed in a desktop-based modality within the Delmia V5-6R2016 software environment, which allows digitalizing the workstation layout and the human operations by virtual manikins. Such a simulation requires a great effort in order to create a robust and realistic simulation: usually numerous working hours have to be spent to have a sequence of actions able to well replicate the real users' movements. Furthermore, video-recorded material taken from real workstations monitoring is necessary: the task is divided into a set of postures, and each posture is re-created manually in the software. The final results highly depend on the subjective impression of experts and by the software knowledge in terms of databases (e.g., libraries for manikins, population data). Such simulation modality represents a first level of digitization for companies willing to human-centred manufacturing. The second simulation is carried out in a mixed reality immersive environment, where tasks are replicated by real users in a virtual environment and tracked by a proper system. In the research, the software architecture is composed by different software: Delmia for workstation digitalization, a tracking system for real users' tracking, a system tool for manikin digitalization and connection among real user movements and virtual manikin movements. At least two experts must be necessarily involved and real users: users act as operators, and their movements are tracked, while two experts are involved in camera configuration, data acquisition and data post-processing.

3.2. The mixed reality simulation environment

The immersive simulation set-up has been realized by the following software architecture: Delmia V5-6 for workstation digitalization, Vicon Tracker for real users' tracking, Catia for manikin digitalization, Haption RTI Delmia for connection among real user movements and virtual manikin movements. From the hardware viewpoint, a set of optic tracking cameras by Vicon is used for motion capture, 3D printed rigid bodies are used for full body marking, and rapid prototyped tools used to create a mixed reality set-up to support the main human-system interaction. After that, a proper workspace is identified according to the number of cameras and the dimensions of the workstation to be simulated. Indeed, the workspace volume has to be reduced in order to capture the movements with a good level of detail. In our case, the simulation workspace was about 3 cubic meters. Once the layout was recreated, the Vicon cameras were positioned in the right configuration to assure a robust tracking of both human body and tracked objects also. Indeed, the configuration has to guarantee that each marker is captured by at least 3 cameras at the same time without blinking or signal loses. After that, 22 rigid bodies were created in order to design a good full body motion capture template. Each rigid body contained at least 4 markers, and is positioned on the as set of pre-defined areas of the devices or body parts to be tracked. The selection of the most proper number of rigid bodies is fundamental for reducing the gap between the tracked body parts and facilitating the correct reconstruction of the user movements reducing errors during data acquisition. Finally, a dedicated suite for motion capture has been created by using the Haption RTI Delmia plugin. It combines a set of rigid bodies associated with the virtual manikin parts. The correspondence between the segments of the virtual manikin and the different body parts of the real operator can be realized in this way, after a proper system configuration. In this way the trajectories of the rigid bodies in the real scene, associated to both the human segments and real objects, can be moved into the virtual environment to reproduce, view and record in real time the movements of the real user within the digital environment. Fig.1 shows the simulation environment: the real workplace tracked by Vicon's cameras and the related virtual environment (A), and the rigid bodies with reflective markers used for tracking both human body segments and real objects into the scene (B). Fig.2 shows the motion capture suite that allows correlating the real human body and the virtual manikins: the virtual manikin body segments' configuration (A), and the rigid bodies' system for full body motion capture (B).

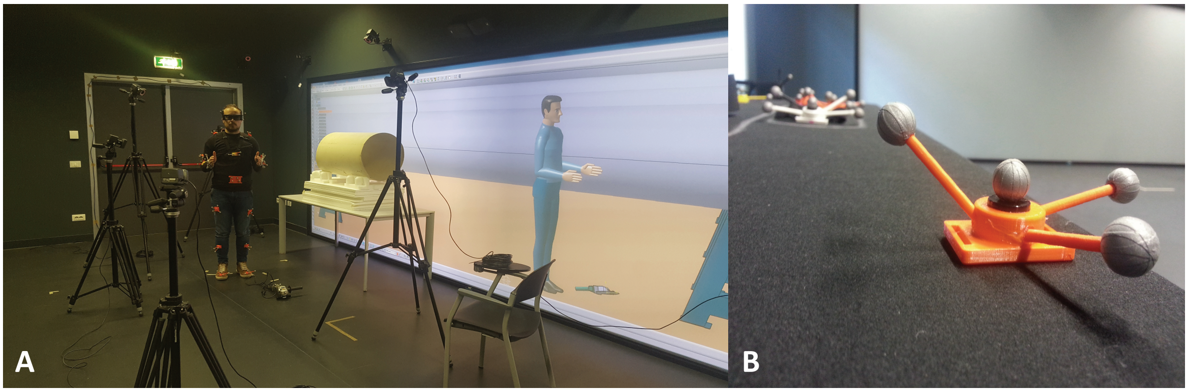

Fig. 1. The virtual simulation environment

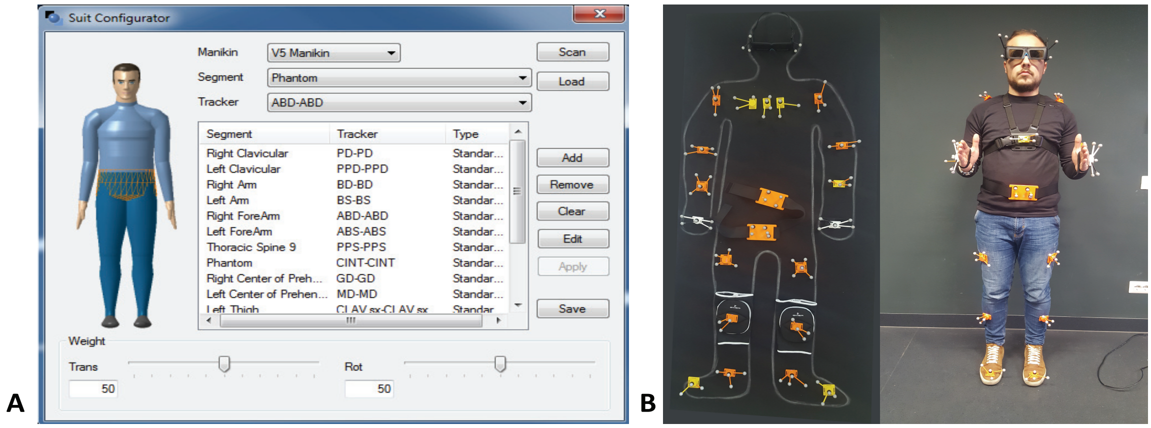

Fig. 2. The motion capture suite

4. The industrial case study approach

4.1. Case study description

The industrial case study has been developed in collaboration with Tenaris Dalmine, the Italian site of the Tenaris SA, a leading global manufacturer of steel pipe products and related services for the world's energy industry and other industrial applications. The study focuses on the design optimization of the quality control workstation, dedicated to dimensional and visual control of OCTG pipes. The analysis started from the existing workplace in order to define re-design actions for future workstations. Such a workstation has been selected for this study due to its presence in all company production sites and the variety of the tasks executed. Indeed, during each single day tasks vary from cleaning the pipe surfaces with compressed air, to controlling the quality of pipe ovalization, until grinding internal and external surfaces. Pipes can also vary in diameters, and such variation greatly affects the workers position during task execution. Furthermore, workers can stand or seat down depending on the specific task.

4.2. Task simulation

Five tasks were simulated during the case study for the selected workstation. Grinding the external surfaces consists of grinding the defects on the external surface of the pipe by using a grinder that is manually handled by the worker. The pipe edge control consists of washing the pipe with a magnetic fluid and using a special lamp to check up the pipe edges' quality. Quality control by pipe ovalization is based on the control of the pipe eccentricity at the end of the production line by a hydraulic pump that is inserted into the pipe by the support of a sliding guide. Grinding of internal surfaces consists of grinding the defects on the internal surface of the pipe; it is more complex since grinder is moved into the pipe by a carriage sliding on dedicated tracks. Finally, internal cleaning eliminates the residual material after pipe manufacturing by compressed air. Two bars with the compressed air are used to treat all the pipe length. Table 1 describes the five tasks simulated during the case study and the variable and fixed parameters considered during the simulations. Variable parameters will vary in a range indicated by the company to model different possible workstation configuration.

Each task was simulated on different pipe diameters and with different design alternatives (e.g., height of the working plane, distance from the working plane). A preliminary site inspection allowed to collect the simulation data, observe the workers during task execution, describe the operative conditions to be reproduced, define the simulation parameters, and describe the workstation design features to be reproduced by virtual models. Simulations were carried out in the virtual environment described in section 3.2.

Table 1. Task simulation for the case study

Task	**Activities**	**Variable parameters**	**Fixed parameters**
Grinding external surfaces	Grinder placement, grinding, grinder replacement.	Pipe diameter, height of the workplace, percentile of the population, nationality.	Weight of the grinder
Pipe edge control	Washing the pipe with magnetic fluid, check up of the pipe with specific lamp, grinding, data insert on terminal.	Pipe diameter, percentile of the population, nationality, lamp placement.	Weight of the devices, height of the workplace.
Quality control by pipe ovalization	Devices pick up, devices placement on the pipe, placement of the support, placement of the jack inside the pipe.	Pipe diameter, height of the workplace, percentile of the population, nationality.	Weight of the devices.
Grinding internal surfaces	Grinder lifting, grinder placement, grinding, grinder replacement.	Pipe diameter, percentile of the population, nationality.	Weight of the grinder, height of the workplace.
Internal cleaning	Sliding, lifting and placement of the first device, sliding, lifting and placement of the second device, pushing devices inside the pipe.	Pipe diameter, percentile of the population, nationality, weight of devices.	Height of the workplace and of the devices support.

4.3. Results and discussion

Real users were tracked during task execution, their real movements were moved into the virtual environment on virtual manikins and a virtual sequence of actions was obtained in this way. After that, each sequence of actions corresponding to a specific task was divided into a set of "move to posture" (MTP), in order to discretize the analysis. For each MTP different data were collected to carry out a physical ergonomic analysis. Such analysis is compared with those one carried out in a simpler desktop-based environment and by traditional assessment based on real operators' observation and checklist carried out by experts. Fig.3 shows the results analysis comparison for two physical stress indicators: RULA on the right and left side of the human body, and the force compression on L4-L5 lumbar vertexes, for one of the analysed tasks (i.e. grinding on external surfaces).

Fig. 3. Example of simulation results for the case study: comparison among different simulation modality (based on mixed reality immersive environment, desktop-based and observation of real users)

The comparison of the preliminary simulation results collected for the case study tasks highlighted the main difference in simulation efforts and data accuracy. Indeed, the quality of the results collected in the mixed reality environment was higher than desktop modality, and the human motion simulation was more accurate. Furthermore, for the mixed reality simulation higher level of detail for each simulated posture can be achieved with low effort. Indeed, each posture can be easily and quickly acquired by the motion capture system to have a more precise and realistic simulation. As a consequence, results are closed to observation of real workers. At the same time, results can be retrieved on digital workstations before real system creation, supporting alternative validation and definition of new design issues. In this sense, the mixed reality simulation modality has been proved to represent an advanced level of digitization for modern companies in the context of human-centred manufacturing: it allows digitalizing the workplace to be optimized and replicated the human-system interaction in a detailed way with low effort and high results quality.

5. Conclusions

The paper demonstrated the benefits of a virtual simulation by the use of an immersive simulation environment adopting virtual reality technologies and mixed prototyping, merging real and virtual objects, to optimize the physical ergonomics in workstation design. The study proposed a simulation approach and compared the results obtained between different environments. In particular, it compares results obtained in a desktop modality using Delmia V5-6 tool, in a mixed reality immersive virtual environment using Delmia V5-6, Haption RTI plug-in and a Vicon optical system for motion capture and object tracking, and real practice based on real operators' observation and traditional ergonomic assessment based on checklist and experts' evaluation. The approach is tested on an industrial case study developed in collaboration with a leader company in energy industry for the optimization of the social sustainability of its workstations. The immersive virtual simulation was proved to support re-design actions by anticipating the human factors assessment during the design stage by involving real users, validating the plant layout, and improving the overall process quality.

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