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Published Version:
Peruzzini, M., Carassai, S., Pellicciari, M., Andrisano, A.O. (2017). Human-centred design of ergonomic workstations on interactive digital mock-ups. BERLIN : SPRINGER-VERLAG BERLIN [10.1007/978-3-319-45781-9_119].

Availability:
This version is available at: https://hdl.handle.net/11585/955974 since: 2024-02-06

Published:
DOI: http://doi.org/10.1007/978-3-319-45781-9_119

Human-centred design of ergonomic workstations on interactive digital mock-ups

Margherita Peruzzini[1*], Stefano Carassai[1], Marcello Pellicciari[1], Angelo Oreste Andrisano[1]

[1] Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, via Vivarelli 10, 41125 Modena, Italy

* Corresponding author. Tel.: +39 059 2056259; fax: +39 059 2056129. E-mail address: margherita.peruzzini@unimore.it

Abstract Analysis of human-related aspects is fundamental to guarantee workers' wellbeing, which directly limits errors and risks during task execution, increases productivity, and reduces cost [1]. In this context, virtual prototypes and Digital Human Models (DHMs) can be used to simulate and optimize human performances in advance, before the creation of the real machine, plant or facility. The research defines a human-centred methodology and advanced Virtual Reality (VR) technologies to support the design of ergonomic workstations. The methodology considers both physical and cognitive ergonomics and defines a proper set of metrics to assess human factors. The advanced virtual immersive environment creates highly realistic and interactive simulations where human performance can be anticipated and assessed from the early design stages. Experimentation is carried out on an industrial case study in pipe industry.

Keywords: Human-Centred Design; Ergonomics; Sustainable Manufacturing; Digital Human Model; Virtual Reality.

1 Introduction

In recent years a lot of attention is paid to sustainable products and processes by mainly focusing on environmental and economic aspects to limit costs and resource consumption [2-3]. Although several studies demonstrated how much the industrial plant's costs and productivity highly depend on human physical and mental efficiency, hazardous positions and uncomfortable tasks, and how much the risk of developing musculoskeletal disorders for workers costs to the company [4], the role of human factors on sustainability has been largely underestimated so far. It has been demonstrated that improving human-related aspects in industry is fundamental to guarantee workers' safety and wellbeing, which directly affect company productivity, consumed resources, and expenses [1]. As far as the evaluation of environmental and cost performance during the design stages, a huge literature has been developed in recent years [5-7]; contrarily, as far as early human factors assessment, there are no structured and robust practices in industry. Due to the importance of human-related issues to achieve high-quality and cost-effective processes, and the lack of industrial practices in this direction, the present paper focuses on the early assessment of human performance during manufacturing and operation processes. It aims to provide an early assessment of physical and cognitive ergonomics from the conceptual design stages, where cost for engineering changes is lower and the innovation potential is higher. In particular, the paper defines a human-centred methodology to be applied on digital mock-ups by interactive, immersive and real-time virtual simulation. Within the virtual environment, tasks can be simulated and, consequently, the workstation design optimized according to ergonomics principles.

2 Related works

Human-Centred Design (HCD) consists of the application of human factors' information (i.e., physical, psychological, social, biological human characteristics) to the design of tools, machines, systems, tasks, jobs, and environments, for safe, comfortable, and effective human use [8]. The analysis of human factors in manufacturing is a novel research trend, but it is revealing extremely important to optimize human performances, health, and safety. Indeed, numerous studies have recently demonstrated the great economic impact of work-related musculoskeletal disorders for both companies and societies, all over the world [9-10]. From literature review, two main aspects emerged: 1) human-related topics are still poorly introduced in industrial contexts; 2) the majority of works usually are verification and validation studies, where human factors are measured at the end of the design process after the system development, on real plants or machines by traditional approaches. Traditional approaches are based on the observation of individual workers performing their jobs in order to detect unnatural postures and define corrective actions according to physical ergonomic guidelines. Different tools have been defined during the years, based on the posture observation and assessment of physical exposures (i.e., NIOSH, OWAS, RULA, and REBA) [11]. Analyses are usually carried out on real workstations, when operators are already working on them, and corrective actions are taken late, so they are limited and expensive.

Nowadays, virtual prototypes can validly reproduce industrial workplaces with high fidelity, before their real creation, and simulate human performance by digital manikins replicating the human actions. Different digital models are today included into several commercial software toolkits, from SAFEWORK (by Dassault Systèmes) to JACK (by Siemens) available on Siemens / Technomatix products, until specific software for particular applications (SANTOS, 3DSSPP or Anybody

Modeling System) [12]. Human models can also be coupled with multi-body and finite elements' analyses to obtain quantitative information on human-object interaction [13]. Such tools can support preventive design optimizations, but they have some limitations:

- time-consuming, since preparing realistic and reliable simulations usually takes time and significant effort;
- low realism, due to low aesthetic rendering and low realism of the simulated scene (e.g. lack of physical object behavior, lack of collisions, etc.);
- lack of cognitive ergonomic evaluation, since they only include postural models and do not assess the subjective impressions of real workers.

In this context, VR technologies provide immersive environments that enable users to navigate the virtual scene and interact with products or systems [14]. Reach, visibility, and visual inspection are possible using an immersive modality. The so-called user experience, intended as the compendium of physical efforts and subjective perceptions (e.g., predispositions, expectations, needs, motivation, mood, etc.) that generates the human response according to the characteristics of the designed system (i.e., complexity, purpose, usability, functionality, etc.) and the context of use [15], is simulated by real-time task execution. However, a VR scene is not enough to efficiently assess the user experience, since it requires to be coupled with a proper assessment protocol analysis. Recent studies also proposed Augmented Reality (AR) environments that support the user to interactively see virtual and physical objects and to access additional data in real time for different applications (i.e., service and maintenance) [16]. Although results confirmed the feasibility and exploitability of such methods from a technological point of view, they do not support system design focusing of the human experience.

2 The human-centred design methodology

In order to support early assessment of human factors for industrial workstation on virtual models, a human-centred methodology is firstly defined. It considers the final response as the combination of both physical and cognitive aspects and defines a set of evaluation metrics to elicit the user experience. Such metrics can be measured on both traditional prototypes (physical mock-ups) and interactive and immersive virtual mock-ups, where all the aspects characterizing the real experience lived by users can be properly reproduced. The novelty of the present study is the adoption of the protocol analysis coupled with immersive virtual prototyping for the specific investigation of industrial workstations. It exploits 3D modeling tools and a VR laboratory to create an immersive and interactive digital environment where users can simulate in real-time their tasks on an interactive workstation model. The VR set-up used is described in the following paragraph. The proposed method can be summarized in six main steps:

1. Creation of a functional 3D mock-up of the workstation according to the process requirements (e.g., plant layout, activity scheduling, etc.);
2. Definition of a set of design and task parameters: design parameters refer to the workstation features (e.g., height of the working surface from the worker's feet, distance of the working point from the worker body, inclination of the working planes, etc.), and their a range of variation, while task parameters refer to specific conditions (e.g., weights to move, intermediate positions, etc.);
3. Real time simulation of task execution within an immersive and interactive VR environment, with the involvement of workers and experts;
4. Assessment of human factors by the investigation of both objective and subjective metrics, as described in the protocol analysis (Table 1);
5. Definition of the most critical postures and tasks and recognition of the most critical features of the workstation affecting the human factors' assessment;
6. Design optimization by acting on the design parameters in order to limit the impact on human factors and promote the system ergonomics.

Table 1. Protocol analysis for human factors' assessment.

Analysis	*Metrics*	*Unit of meas.*	*Data collection techniques*
Posture	Physical comfort	RULA and REBA score (no.)	Ergonomic analysis Heuristic evaluation
Occlusion	Visibility	View cones (deg.)	Ergonomic analysis Heuristic evaluation
	Accessibility	Distance between the user and reached zones (mm)	
Mental load	Ease of use	Requests of support (no.) Action sequence steps (no.)	Ergonomic analysis Heuristic evaluation
	Mental workload	Fatigue or distraction behaviors (no.)	
Interaction	Feedback	Visual, tactile and auditory feedbacks (no.)	Ergonomic analysis Heuristic evaluation
	Interaction support	Affordances (no.) Task completion ratio (user/expert) (s)	Ergonomic analysis Heuristic evaluation
	Information quality	Errors frequency (%)	Ergonomic analysis Heuristic evaluation
Emotions	Satisfaction in use	Subjective impression score (no.)	Heuristic evaluation Interview

The assessment of human factors is based on the Norman's model of interaction [17], assuming that any system, with which the user interacts, determines the user actions and communicates with humans by means of two different types features: "affordances", which stimulate a precise action in the user (e.g. an handle that suggest the action of handling), and "synaesthesias", which stimulate visceral sensations, emotions, memories and mental associations related to the human affective sphere. Five different analyses are defined: *Posture*, *Occlusion*, *Mental Load*, *Interaction*, and *Emotions*. Physical human responses are assessed by *Postural* and *Occlusion* analyses; affordance support, which stimulates the behavioral response by promoting specific actions to be taken related to task efficiency and effectiveness, is measured by *Mental Load* and *Interaction* analyses; finally, synaesthesias influence, which affects information comprehension and satisfaction in use, is measured by *Emotions* analysis. For each analysis, a set of evaluation metrics has been defined (Table 1). About data collection, postural data are calculated by combining DHM tools export and post processing, using Excel and Matlab; diversely, user behaviors and reactions are investigated by heuristic evaluation and interview, widely used in HCD. Heuristic evaluation is based on users' direct observation to capture moment-to-moment interactions, verbal comments, and non-verbal communication (gestures, expressions, etc.). Interview retrieves information directly from users, who correlate their preferences with metrics values. The inverse 1-5 points Likert scale is chosen to assign a value to each metrics indicators both for heuristic evaluations and interviews (1 = good, 5 = bad). Experts in ergonomics are involved to observe users and evaluate the specified metrics. Collected data are analyzed according to the existing international regulations (i.e. UNI EN ISO 9241-210, ISO/DIS 10075-1, UNI EN 894) [8, 18-19].

4 The VR immersive and interactive set-up

The research exploits the facilities of the ViP Lab (Virtual Prototyping Lab) of the Modena Technopole, where a VR set-up allows creating high-fidelity virtual prototypes of the entire production line and the specific workstations, in order to simulate them into an immersive and interactive environment. The adopted set-up consists of a Steward large volume display (6x2 meters) with rear projection, two high-performance Barco Galaxy NW-7 projectors, active stereo glasses with active Volfoni Edge RF, an high-quality Vicon optical tracking system (with 8 cameras), two Nintendo Wiimote devices for interactive navigation, a Denon AVR sound system with Dolby surround, and advanced toolkits for system modeling (CATIA and DELMIA by Dassault Systemès) and immersive virtual simulation and human modeling (IC.IDO by ESI Group [20]). Such a set-up allows high-quality stereoscopic and immersive virtual simulation to reproduce virtual objects into a 1:1 scale, create highly realistic simulations, and validate static and dynamic behaviors during preliminary design. The large volume display also support collaborative design activities. As far as digital mock-ups creation, the 3D models of the industrial plant and the workstations can be realized by using different 3D CAD software (e.g., CATIA V5, JT, PLMXML, Pro/Engineer, SolidWorks, etc.) and imported directly into IC.IDO software. After that, the interactive scene is created within IC.IDO by defining the "touchable" objects and the environmental constraints (e.g., collisions, gravity, etc.). Multiple scenes can be created with different properties. The user can interact directly with the virtual objects by Wiimote devices, and in addition he/she can be linked to an avatar that reproduces his/her movements in real time. It can be realized by connecting some points or devices, tracked by the Vicon system, with the avatar joints. For instance, the Wiimotes can be linked to the avatar's hands or the handled devices (i.e., screwier, gauge, etc.) while markers fixed on the user's arms, legs, wrists and feet can be linked to the same avatar's body parts.

5 The industrial case study

The industrial case study has been developed in collaboration with Tenaris S.A., a leading global manufacturer of steel pipe products for energy industry. The study focuses on the optimization of the quality control workstation, where workers visually and dimensionally check pipes by different tasks (e.g., cleaning the pipe surfaces with compressed air and water, controlling the quality of threads, deburring the black crest, grinding some surfaces, measuring the final dimensions). Pipes can vary in diameter and position, and the worker can stand or seat depending on the specific task. According to the company requirements, analyses focused on ***grinding*** and ***control with gauge***. CATIA and DELMIA toolkits were used to model and simulate the plant layout and the workstation design features. Subsequently, the virtual scenes were prepared in IC.IDO considering the real sequence of actions and interaction capabilities with the workstation items (device, pipe, etc.). Finally, the user (simulating the real worker) was equipped with tracked stereo glasses and devices (i.e., Wiimotes), which represent the handled tools, and linked with the virtual manikin in IC.IDO. In this way, the user can directly interact with the virtual scene, according to the real production constraints and events, while the virtual manikin moves according to his/her positions (Figure 1)..

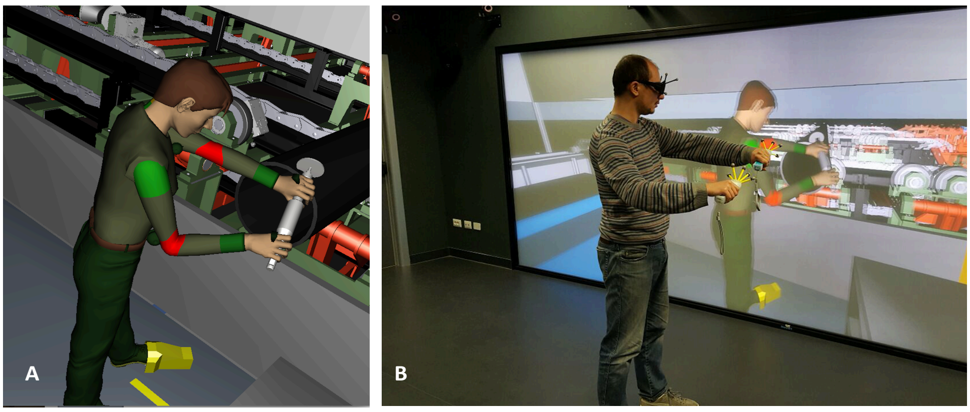

Fig. 1. Task simulation (e.g. grinding): virtual manikin (A) and real user experience within the VR set-up (B)

Two experts in ergonomics were involved for users' observation, interviews and ergonomic analysis, to carry out the human factors' assessment according to the proposed protocol. 20 users were involved in the simulation. Table 2 shows the summary of the results (average on 20 users) for some postures (P), on the original workstation design. Scores in Table 2 are expressed according to an inverse 5-point scale: they combine the results from ergonomic analysis and heuristic evaluation, and interview to users as far as satisfaction metric is concerned, according to the protocol presented in Table 1. For each posture (P), the score indicates the average ergonomic performance for the specific metric. The last column (All P) is the average on the 20 postures analyzed. Scores higher of 3 represent critical values and are marked in red. From Table 1, it can be inferred that grinding is particularly stressful for users due to uncomfortable positions (3,50 score on average), poor visibility (3,10 score on average), and mental workload (3,40 score on average). Furthermore, also information quality and satisfaction in use could be improved (respectively 2,95 and 2,70 scores on average). Consequently, also easy to use (2,60 score on average) could be optimized. As far as the second task, control with gauge, the critical issues refer to the perceived comport (4,20 score on average) and the mental workload (3,00 score on average).
According to the experimental results, the workstation design was optimized in order to increase the user experience measured by the proposed protocol. Attention was paid to the critical issues emerged from Table 2, and the workstation was re-designed by the following actions:

- height of the pipe was increased;
- distance to the pipe was reduced;
- the sequence of actions to be carried out were simplified (each task was reduce to maximum 4 actions).

Table 2. Assessment of human factors within the VR immersive set-up (average on 20 users).

		GRINDING (2 kg)				***CONTROL WITH GAUGE (1 kg)***			
Analysis	**Evaluation metrics**	***P1***	***P7***	***P15***	***All P***	***P1***	***P2***	***P4***	***All P***
Posture	Perceived comfort	4,3	4,1	2,4	**3,50**	5	4,5	4	**4,20**
Occlusion	Visibility	4	4	1,5	**3,10**	2	2,5	2,4	**2,25**
	Accessibility	2	2	1,5	**1,80**	1,5	2	2	**1,80**
Mental Load	Ease of use	2,9	3,2	1,5	**2,60**	1	3,6	3	**2,55**
	Mental workload	3,6	4	2,5	**3,40**	2	3,6	3,3	**3,00**
Interaction	Feedback	2,6	2,8	1	**2,10**	2	2,8	2,2	**2,30**
	Interaction support	2,4	2,7	1	**2,00**	2	3	2,6	**2,50**
	Information quality	3,4	3,5	2	**2,95**	2	2,6	2,4	**2,30**
Emotional	Satisfaction in use	3	3	2,2	**2,70**	2	3,1	2,7	**2,60**

Table 3 shows the comparison between the scores obtained on the original design and the new design. In particular for grinding, the actions taken allowed to reduce the impact on human factors in terms of comfort perceived (from 3,50 to 2,50 score on average), visibility (from 3,10 to 1,60 score on average) and mental workload (from 3,40 to 2,50 score on average). Also other metrics will be positively affected by design changes, such as Information quality and ease to use), By measuring the process performance, the positive impact of such ergonomic improvements are elicited in terms of time (-10%), productivity rate (+5%) and costs (-12%). The design changes positively affected also the second task, control with gauge. In particular, the perceived comfort (from 4,20 to 3,00 score on average) and the mental workload (from 3,00 to 2,50 score on average) were improved, but also visibility, ease to use, feedback, interaction support and satisfaction in use were improved. Also in this case, the new solution allowed improving the ergonomic performance and consequently the process sustainability in terms of lower execution time (-12%), higher productivity (+8%) and lower global production costs (-15%).

Table 3. Result comparison between original design (D1) and optimized design (D2) (average on 20 users).

		GRINDING		***CONTROL WITH GAUGE***	
Analysis	**Evaluation metrics**	***D1***	***D2 (new)***	***D1***	***D2 (new)***
Posture	Perceived comfort	3,50	**2,50**	4,20	**3,00**
Occlusion	Visibility	3,10	**1,60**	2,25	**1,60**
	Accessibility	1,80	**1,80**	1,80	**1,80**
Mental Load	Ease of use	2,60	**2,50**	2,55	**2,50**
	Mental workload	3,40	**2,50**	3,00	**2,50**
Interaction	Feedback	2,10	**2,10**	2,30	**2,00**
	Interaction support	2,00	**2,00**	2,50	**2,30**
	Information quality	2,95	**2,50**	2,30	**2,30**
Emotional	Satisfaction in use	2,70	**1,50**	2,60	**1,80**
	Execution time*	30 sec	**-10%**	45 sec	**-12%**
Sustainability	***Productivity****	NDA**	**+5%**	NDA**	**+8%**
	Production costs*	NDA**	**-12%**	NDA**	**-15%**

****simulated values, to be confirmed on plant   **data cannot be published due to NDA (Non Disclosure Agreement)***

6 Conclusions

The research combined a protocol to assess human factors with an advanced VR set-up to support the design of ergonomic manufacturing workplaces the early design stages on digital mock-ups. The protocol is based on the evaluation of physical and cognitive aspects of the user experience, while the VR set-up allows creating highly realistic and interactive virtual environments where users can interact with the digital workstation. An industrial case study is presented. Experimental results demonstrated how the improvement of the workstation ergonomics brings to a higher process sustainability, and how the joint action of a proper methodology and a suitable VR set-up can effectively support companies in designing ergonomic workstations. Future work will be focused on verifying the results achieved by simulation on the real plant and to define a design set of guidelines for sustainable manufacturing.

Acknowledgments The authors want to acknowledge ESI Group (www.esi-group.com) and Tenaris (www.tenaris.com) for their precious collaboration.

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