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A comparative study on computer-integrated set-ups to design human-centred manufacturing systems

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ABSTRACT

Manufacturing ergonomics refers to the application of ergonomic principles and human factors analysis to the design of manufacturing tasks with the final aim to optimize the workers' wellbeing and guarantee the expected process performance. Traditional design approaches are based on the observation of individual workers performing their jobs, the detection of unnatural postures (e.g., bending, twisting, overextending, rotating), and the definition of late corrective actions according to ergonomic guidelines. Recently, computer-integrated simulations based on virtual prototypes and digital human models (DHMs) can be used to assess manufacturing ergonomics on virtual manikins operating in digital workplaces. Such simulations allow validating different design alternatives and optimizing the workstation design before the creation, and pave the way to a new approach to manufacturing system design. The present paper aims at comparing different computer-integrated set-ups to support the design of human-centred manufacturing workstations. It defines a protocol analysis to support workstation design by analysing both physical and cognitive aspects, and applies the protocol within different digital set-ups. In particular, the study investigates a 2D desktop set-up using standardized DHMs and a 3D immersive mixed reality set-up based on motion capture of real workers' acting into a mixed environment, comparing them with the traditional approach. An industrial case study focusing on design optimization of a manufacturing workstation in the energy industry is used to test the effectiveness of the two digital set-ups for the definition of re-design actions.

1. Introduction

Many manufacturing companies are becoming interested in ergonomics and human factors while designing their products and processes, focusing on how humans behave physically and psychologically in relation to particular environments, products, or services. Such a discipline is called "manufacturing ergonomics" and aims at reducing both mental and physical workload. The final scope is to optimize the workers' actions, improve their safety by preventing musculoskeletal disorder (MSD), control and manage their physical and mental workload, and guarantee the expected process performance [17]. The interest of manufacturing companies to human-related aspects is growing worldwide 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. Generally, poorly ergonomic processes usually generate high costs for societies as demonstrated in Europe and United States [4,32]. 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 [9,14,25].

Ergonomic analyses on workplaces are traditionally based on the observation of workers when the production line is already running, so they are time-consuming and not preventive. Nowadays, there are emerging technologies supporting human-centred simulation based on

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preventive workplace ergonomic validation. Such tools allow the workplaces and the tasks to be simulated even before the facilities are physically in place and the ergonomic principles to be applied on digital human models (DHMs) during the early design stages for proactive investigation [6]. These tools provide a quick, virtual representation of human beings in a simulated working environment and can be used to identify the ergonomic problems and prevent MSD risk. 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 research presents an example of an industrially relevant computer-integrated manufacturing technology, based on digital manufacturing. The purpose of the research is to adopt digital manufacturing tools to support manufacturing ergonomics by comparing different computer-integrated set-ups to support the human-centred design (HCD) of workplaces on digital models. For this purpose, the authors define a protocol analysis for ergonomics risk assessments including both functional and cognitive aspects to objectify the measures during the computer-integrated simulations of manufacturing workplaces. The protocol has its foundations on cognitive engineering and the Norman's mental model of interaction [28], where both physical and cognitive workloads are considered. For each analysis, a set of evaluation metrics is defined and different collecting data methodologies are used, including a digital manufacturing software tool, heuristic evaluation and direct interview. Such a protocol is used to assess ergonomic performances within the traditional modality based on users' observation and experts' evaluation on checklist, and two digital simulation set-ups with different levels of immersion and technological complexity: a 2D desktop-based digital set-up where virtual simulations are carried out by DHM tools, and 3D mixed reality immersive environment where virtual and real objects are combined to create a more realistic environment by involving sample users interacting with it. The two digital set-ups have been applied to simulate workers' tasks on manufacturing workstations and to define the re-design actions according to HCD principles. Experts in manufacturing equipment design and ergonomics have been involved to analyse the actual designs and to propose human-centred re-design actions by the support of the different digital set-ups. The results have been compared with the traditional analysis carried out on the real workstation. The effectiveness of the simulation set-ups has been compared and the main strengths and weaknesses of the different procedures have been highlighted on the basis of the experimental results. Finally, the adoption of the proposed approach is discussed with regard to feasibility for companies and related costs and efforts.

2. Research background

2.1. Analysis of human factors in manufacturing

Human factors have a central role in design as the theoretical understanding of human behaviours and performance interacting socio-technical systems and the application of that understanding to design of interactions [39]. Within a manufacturing context, the result of such interaction is the workers' workload, which may be divided in mental demands and physical demands [17]. In particular, physical workload is defined as tasks which require that the workers' muscles work, with the participation of the musculoskeletal, cardiorespiratory and nervous systems [37], while mental workload is a multidimensional concept depending on the workers' personal characteristics (e.g., experiences, attention and skills) and the task features as well as work procedures [40]. Many tasks in the workplace or product design (i.e., assembly features) impose a physical workload, which in turn places loads on mental tasks and cognitive resources [33].

The so-called work-related musculoskeletal disorders (WRMSDs) have been defined as the most costly occupational problems, and cause significant human suffering and economic burdens for employers, workplaces, workers and society [3]. As a consequence, the accurate measurement of workers' exposure to the factors that may contribute to the development of WRMSDs is of vital importance to both epidemiologists and ergonomists. WRMSD are caused by many factors, including awkward postures (e.g. bending, stretching, twisting), repetitive movements, using force and manual handling (lifting and carrying) working hours, static postures and repetitive nature of work were identified as some of the risk factors leading to pain and discomfort [29]. WRMSDs have also heavy economic costs to companies and to healthcare systems. The costs are due to loss of productivity, training of new workers and compensation costs.

As a consequence, an ergonomically[30] deficient workplace can cause physical and emotional stress, low productivity and poor quality of work. Assessment of exposure levels to WRMSD risk factors can be an appropriate base for planning and implementing interventional ergonomics programs in the workplace. For instance, 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 WRMSDs, with a great economic impact on both companies and societies. Indeed, providing a workplace free of ergonomic hazards can bring numerous advantages: lower injury rates as WRMSD incidences go down, increased productivity by making jobs easier and more comfortable for workers; improved product quality because fewer errors will be made when using automated; faster and safer processes, due to less physical effort demand; reduced absences because workers will be less likely to take time off to recover from muscle soreness, fatigue, and WRMSD-related problems; reduced turnover as new hires are more likely to find an ergonomically designed job within their physical capacity; lower costs as workers' compensation and other payments for illness and replacement workers go down; increased worker comfort and reduced worker fatigue; and improved workers' motivation.

In order to reduce WRMSD risks, many methods have been developed to investigate ergonomic design problems. Traditional methods for ergonomic analysis were based on statistical data obtained from previous studies or equations based on such studies. An ergonomics expert was required to interpret the situation, analyse and compare with existing data, and suggest solutions. During the years, different analytical tools have been defined. These methods can be mainly classified into objective and subjective evaluation methods [22]. Objective methods are based on the posture observation and objective assessment of physical exposures, such as NIOSH lifting equation [7], Ovako Working posture Analysis System (OWAS) [19], Occupational Repetitive Actions (OCRA), Rapid Upper Limb Assessment (RULA) [26], Rapid Entire Body Assessment (REBA) [15] or Workplace Ergonomic Risk Assessment (WERA) [34]. Traditionally such methods are used to assess physical ergonomics from direct observation on prototypal workstations or real industrial lines, which is usually time-consuming, difficult to carry out and objectify, and provides results when the project has been completed and sometimes the manufacturing line is running. Nunes and McCauley Bush [30] provided a review about how to adopt the above-mentioned tools to assess WMSD. An efficient approach is to identify occupational risk factors by using RULA, OWAS, REBA, etc. and make efforts to remove them from task. Diversely, subjective methods focus on the physical response of the human beings involved in the tasks under investigation and aim at evaluating the human efforts and discomfort in task execution, such as the Rated Perceived Exertion (RPE) method based on the Borg's scale and the Body Part Discomfort (BPD) [23].

Obviously, the manufacturing ergonomics is strictly linked to the