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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.

Keywords: manufacturing ergonomics, human factors, digital human models, human-centred design, mixed reality.

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 (Hwang et al., 2008). 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 (Buckle and Devereux, 1999; NRCIM, 2001). 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 (Maudgalya et al., 2008; Hendrick, 2008; Dul and Neumann, 2009).

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 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 (Demirel and Duffy, 2007). 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 (Norman, 2008), 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 (Wilson, 2000). Within a manufacturing context, the result of such interaction is the workers' workload, which may be divided in mental demands and physical demands (Hwang et al., 2008). 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 (Sluiter, 2006), 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 (Young and Stanton, 2004). 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 (Perry et al., 2008).

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 (Broberg et al., 2014). 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 (Nunes, 2009). 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 (Nunes and McCauley Bush, 2012).

As a consequence, an ergonomically 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 (Li and Buckle, 1999). Objective methods are based on the posture observation and objective assessment of physical exposures, such as NIOSH lifting equation (Dempsey, 2002), Ovako Working posture Analysis System (OWAS) (Karhu et al., 1981), Occupational Repetitive Actions (OCRA) (Occhipinti, 1998), Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett, 1993), Rapid Entire Body Assessment (REBA) (Hignett and McAtamney, 2000) or Workplace Ergonomic Risk Assessment (WERA) (Rahman et al., 2011). 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 (2012) 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 (Kim et al., 2004) and the Body Part Discomfort (BPD) (Lin et al., 2010).

Obviously, the manufacturing ergonomics is strictly linked to the manufacturing system design. Indeed, the industrial work environment has to be designed for moving materials and fixing machines effectively. In this context, ergonomics has a critical driving factor. After the advent of the so-called Toyota Production System (TPS), a new way of thinking, based on lean process, zero waste, reducing costs, and the worker welfare, began. Lean Manufacturing promoted to insert other tools that aid, such as: Kaizen, 5 Senses, Poka-Yoke, Takt-Time, Balancing stations or workstations, supply flow of parts and products, Flow Mapping Value, etc. In the application of Lean Manufacturing should be made a direct correlation between vision of working conditions with a support tool mentioned the ergonomics (Adler et al, 1997). Each continuous improvement held in any work environment, this correlation could be carried out in order to adapt the improvements to the executor of activities (Dos Santos et al., 2015). Recently, a model to integrate ergonomics issues and lean and six sigma principles has been proposed (Nunes, 2015).

Such methods, both objective and subjective, are focused on the physical response of the human beings involved in the tasks under investigation. However, theories about human-machine interaction demonstrated that communication between humans and any system is characterized by a behavioural and a cognitive response. The features of the system interacting with the user can be divided in two different types: "affordances" if they stimulate a precise action in the user (e.g., an handle that suggest the action of handling) (Norman, 2008) and "synaesthesias" if they stimulate visceral sensations, emotions, memories and mental associations related to the human affective sphere (Kalviainen, 2002). Therefore, ergonomics can be divided into functional ergonomics, mainly related to efficacy and effectiveness, and cognitive ergonomics regarding user satisfaction and information processing. Several efforts have been made to analyse the process of functional and cognitive responses during human-product interaction in different contexts (Mengoni et al., 2008; Salvendy and Karwowski, 2010). Diversely, in the context of manufacturing, such aspects are still poorly explored and there is a lack of methodologies integrating physical ergonomics and cognition to drive system design. Furthermore, conventional methods for ergonomic evaluation are generally applied for validation and verification, at the end of the design process once the final prototype has been realized and tested with users. Such testing requires a great deal of effort and an expensive physical mock-up and inevitably provides a late response. As a consequence modifications are time-consuming and expensive.

2.2 Computer-integrated digital manufacturing for human factors analysis

In the last two decades, the so-called Digital Human Models (DHMs) are included in commercial software toolkits for ergonomic analysis. They offer 3D anthropometric manikins consisting of an interior model of the human skeleton and an exterior model of the human body shape, which use forward and inverse kinematics algorithms for simulating postures and movements. A lot of different models have been developed but they are quite similar for structure and functioning (Sundin and Ortengren, 2008). Digital models allow reproducing the human involvement by simulating both complexity and uncertainty to be studied in measurable ways. Different tools are available on the market: Dassault Systèmes' SAFEWORK model included in CATIA and DELMIA, JACK model available on Siemens / Technomatix products, RAMSIS, MADYMO (MAthematical DYnamic Models), SANTOS, 3DSSPP (3D Static Strength Prediction Program) and Anybody Modeling System. Such tools allow the ergonomic assessment on virtual prototypes of the workplace according to the main methods (e.g., RULA, OWAS) and simulation of numerous design alternatives with low impact. However, usually preparing accurate DHM simulations is complicated and time-consuming (Chaffin, 2007). Obviously, they do not provide appropriate methods for cognitive ergonomics.

Moreover, other computer-integrated techniques, such as virtual reality (VR) and more recently mixed reality (MR), have been successfully applied to investigate the impact of the designed items on human actions and reactions (Berg and Vance, 2017). Indeed, VR technologies provide immersive working environments where users can navigate and experience the virtual scene, to be used as a decision-making tool in product design, particularly in engineering-focused businesses. As far as ergonomic studies are concerned, VR can be used for reachability and visibility analysis as well as visual inspection through the use of immersive virtual environments, where the user directly experiences tasks execution. Different VR-based set-ups have been created to simulate and successfully assess different aspects of manual operations in manufacturing workplaces as demonstrated in literature (Hu et al., 2011). Numerous examples have been recently reported for different purposes: to assess suitability of the workstation and equipment provided (Grajewski et al., 2013), to test for feasibility of assembly methods (Marzano et al., 2015), to train the human in the assembly tasks (Gavish et al., 2015), to guide the human while performing tasks (Wang et al., 2016) and to check performance of the human with respect to the predefined tasks (Chen et al., 2017). In many of the studies on VR, ergonomics is an underlying issue (Lawson et al., 2016). According to the parameters of interest, visibility issues, posture assumed by the worker as well as reachability and accessibility can be simulated (Enomoto et al., 2013).

The quality of VR and MR simulations strongly depends on hardware and software equipment, from visualization display, to trackers of human body motions, to the interaction with virtual objects by haptics or tactile devices, to recording of individual motions with respect to the reference objects (Gonzalez-Badillo et al., 2014). In addiction, the intelligent processing of the recorded information to seek patterns and its combination with existing knowledge can support the ergonomic analysis (Wang et al., 2016). At a commercial level, there are already some simulation software enabling scenario creation and first ergonomic analysis within a VR environment, but research to apply them to manufacturing is necessary targeting real industries whilst effective ergonomic analysis set-up to be introduced in industry are still missing.

3. Research approach

3.1 Research methodology

The research methodology is based on the HCD approach, which suggests the "interactive systems development to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors and ergonomics" (ISO 9241-210, 2009). Such an approach focuses on the improvement of the human wellbeing, user satisfaction by leveraging accessibility and sustainability, in order to enhance process effectiveness and efficiency. It counteracts possible adverse effects of use on human health, safety and performance. The HCD approach builds upon participatory action research by moving beyond the users' involvement and producing solutions to problems rather than solely documenting them. The initial stages usually revolve around immersion, observing, and contextual framing in which innovators immerse themselves with the problem and community. In order to compare different set-ups, the research is based on the definition of a protocol analysis to objectify the ergonomic performance assessment, to be used to compare the different set-ups with the traditional one. Such a protocol allows to objectify the users' feedback and to measure the ergonomic performances, both physical and cognitive, among the different set-ups and to compare the experimental data.

Figure 1. Human-Centred Design approach for ergonomic workplace design

3.2 The protocol for human-centred workstation design

The research firstly defines a protocol analysis to effectively measure workplace ergonomics by considering both physical and cognitive aspects. Indeed, in case of workstations, it has been widely demonstrated that both of them contribute to the ergonomic performance and are directly responsible for MSD as well as stress and other uncomfortable situations for workers that cause a reduce productivity and absence from work (Young and Stanton, 2004; Perry et al., 2008). The proposed protocol is defined on the basis of the Norman's models of perception and human-machine interaction (Norman, 2008). It is assumed that any "system" (device or machine item), with which the user interacts, determines the user actions, but also communicates with the user by means of affordances and synaesthesias. Interaction between users and the "system" can be measured by actions, affordances and synaesthesias, and generated feelings in the users during task execution. Indeed, executed tasks mainly determine the physical response by defining the postures assumed and the movements, while the workplace layout affects visibility and accessibility, which highly influence physical ergonomics. Furthermore, object affordances stimulate the behavioural response, so that they promote specific actions to be taken and their effect can be related to task efficiency and effectiveness, and affect both mental load and interaction (Norman, 2008). Finally, synaesthesias suggest the cognitive response, so that they refer to information comprehension and satisfaction in use, and are measured by subjective satisfaction (Kalviainen, 2002). Two types of analysis are defined, referring respectively to the physical workload and the cognitive workload. For each of them, a set of evaluation metrics has been defined. Physical workload is measured by posture analysis, postural assessment based on RULA, and physical stress analysis. Cognitive workload is measured by visibility, simplicity of action analysis, interaction support analysis, and satisfaction. For each metric, the specific data to be measured and the methodologies used for data collection have been defined. Table 1 shows the protocol overview and describes the protocol metrics, measures, collecting data methods, and evaluation rules to which experts refer.

Table 1. Protocol analysis for ergonomic assessment on manufacturing workstations

Type of analysis	Metrics	Measures (unit of measurement)	Collecting data methodologies
Physical workload	Posture analysis	Stooping (deg) Max upper arm flexion (deg) Max upper arm elevation (deg) Head flexion (deg) Head rotation (deg)	Ergonomic analysis (on DHM)
	Postural assessment	RULA score (no.1-7) Comfort subjective score (no.1-7)*	Ergonomic analysis (on DHM) Heuristic evaluation (1-7) Interview (1-7)*
	Physical stress	L4-L5 Compression Force (N)	
Cognitive workload	Visibility	Visibility condition (no.1-7 based on view cones amplitude) Visibility subjective score (no.1-7)*	Ergonomic analysis (on DHM) Heuristic evaluation (1-7) Interview (1-7)*
	Simplicity of actions	Simplicity of actions score (no.1-7) Requests of support (no.) Errors (no.) Simplicity subjective score (no.1-7)*	Ergonomic analysis (on DHM) Heuristic evaluation (1-7) Interview (1-7)*
	Interaction support	Time for task completion in relation to experts (s) Affordances (no.) Interaction support score (no.1-7) Interaction subjective score (no.1-7)*	
	Satisfaction	Satisfaction subjective score (no.1-10)*	

Posture analysis is characterized by the investigation of the body postures during the interaction with the "system" and task execution in general, considering the relations between the physical segments at joints. It considers different measures: body stooping, maximum upper arm flexion and elevation, head flexion and rotation. Postural assessment for manufacturing workstations is based on the RULA technique, which can be carried out by checklist during heuristic evaluation, or by computerized procedures. RULA has been chosen among the available techniques, for its simplicity of application and the reliable results provided for manufacturing tasks at workstations, where the upper limbs are mainly involved (Rahman, 2014). The physical stress is measured by objectifying the level of wellbeing related to each assumed posture. For this purpose, L4-L5 compression force is estimated.

Visibility analysis considers whether devices and symbols are clearly visible for the user. Simplicity of actions combines accessibility, information availability and task complexity, since it defines whether devices and symbols are easily accessible, usable and interpreted, and expresses the ability of the system to make the user detect and process the information necessary to carry out a specified task. Diversely, interaction support expresses the mental stress and strain required to perform a specified task and depends on the absence of ambiguity as well as the interaction support provided by commands and devices, as well as symbols and control buttons. Finally, satisfaction relates to the users' subjective response based on pleasure, involvement and motivation. It combines the emotional analysis with sense of control, reliability and general satisfaction perceived by the worker.

Different collecting data methodologies are used, that combines “external” and “internal” measures. External measures refer to computer-based procedures carried out by DHM software tools (e.g., biomechanical data analysis and dimensional data analysis) and/or heuristic evaluation, carried out by experts observing the scenes. Internal measures are diversely elicited directly from users (e.g., workers during task execution) by interview.

Heuristic evaluation and interview are the most common investigation techniques used in HCD to investigate user behaviours and reactions. Heuristic evaluation is based on the direct observation of users according to international standards about ergonomics and remarkable studies from research. User observation is supported by Video Interaction Analysis (VIA) to capture the users’ behaviours by understanding moment-to-moment interactions and supporting experts in users’ interactions analysis by recording also comments, nonverbal interactions, etc. Interview implies the direct contact with the final users to retrieve useful information to assess the metrics and to correlate the user’s preferences with the metrics values. Experts in ergonomics and human factors observe sample users (i.e., workers or researcher simulating the workers’ actions) involved in task execution and evaluate the specified metrics. An inverse 1-7 points Likert scale is chosen to assign a value to each metrics indicators both for heuristic evaluations and interview judgements (1 = good, 7 = bad). The use of inverse scales allows being compliant with data provided by RULA and other ergonomic evaluation scales.

Table 2 describes the RULA scores, while Table 3 presents the 1-7 point scale adopted for visibility analysis, Table 4 presents the 1-7 point scale adopted for simplicity of action analysis, Table 5 shows the 1-7 point scale adopted for interaction support analysis, Table 6 shows the questionnaire scores and questions used for direct interviews. Questions are asked during or after task execution according to the specific task analysis.

Table 2. RULA scores for postural assessment

Score	**Postural comfort**
1	Posture is very comfortable
2	Posture is acceptable
3	Posture is acceptable but could be improved
4	Posture has to be improved
5	Posture has to be changed
6	Posture is uncomfortable and need to be changed
7	Posture is dangerous and need to be immediately changed

Table 3. Visibility conditions

Score	Visibility condition
1	Open and free field of view when objects / devices to be manipulated are located in the middle in a range of ±5 deg horizontally and vertically
2	Open and free field of view when objects / devices to be manipulated are located in a range of ±15 deg horizontally and vertically
3	Open field of view when objects / devices to be manipulated are located in a range of ±30 deg horizontally and ±15 deg vertically
4	Open field of view when objects / devices to be manipulated are located in a range of ±30 deg horizontally and ±30 deg vertically
5	Open obstructed field of view when objects / devices to be manipulated are located in a range of ±45 deg.
6	Partially obstructed field of view when objects / devices to be manipulated are located in a range of ±45 deg.
7	Obstructed field of view when objects / devices to be manipulated are difficulty visible

Table 4. Simplicity of actions scores

Score	Simplicity of actions level
1	No ambiguity, limited number of steps (<2 per task), No errors
2	No ambiguity, limited number of steps (<3 per task), No errors
3	Limited ambiguity, medium number of steps (3-5 per task), No errors
4	Limited ambiguity, numerous steps (>5 per task), No errors
5	Limited ambiguity, numerous steps (>5 per task), Errors rarely occur
6	Ambiguity, numerous steps (>5 per task), Errors can occur
7	High ambiguity, numerous steps (>5 per task), Errors frequently occur

Table 5. Interaction support scores

Score	Interaction support level
1	No ambiguity, Optimal use of affordances, No errors
2	No ambiguity, Good use of affordances, No errors
3	Limited ambiguity, Medium use of affordances, No errors
4	Limited ambiguity, Poor use of affordances, No errors
5	Limited ambiguity, No use of affordances, Errors rarely occur
6	Ambiguity, No use of affordances, Errors can occur
7	High ambiguity, Wrong use of affordances, Errors frequently occur

Table 6. Questionnaire for users (during or after task execution)

Type	Question	Scale
Comfort subjective score (no.1-10)	1. Do you feel in a comfortable position?	1 = very comfortable 10 = very uncomfortable
	2. Are your upper limbs in a comfort position?	1 = very comfortable 10 = very uncomfortable
	3. Are your neck and your head in a comfort position?	1 = very comfortable 10 = very uncomfortable
	4. Are your lower limbs in a comfort position?	1 = very comfortable 10 = very uncomfortable
Visibility subjective score (no.1-10)	5. Can you see everything you need?	1 = yes, perfectly 10 = no, nothing
Simplicity subjective score (no.1-10)	6. Is your task simple to execute?	1 = yes, very simple 10 = no, very difficult
Interaction subjective score (no.1-10)	7. Do you have a set of interaction cues helping to execute the task?	1 = yes, very much 10 = not at all
	8. Do you like the kind of interaction support?	1 = yes, very much 10 = not at all
Satisfaction subjective score (no.1-10)	9. Are you satisfied of task execution?	1 = yes, very satisfied 10 = not, very dissatisfied

3.3 The computer-integrated simulation set-ups

The proposed research is based on the adoption of two digital simulation set-ups to support human-centred design of manufacturing workstations. In both cases, the workstations are digitised by computer-integrated tools, and a detailed 3D virtual model is created for each of them. The virtual model considers the entire production line layout, the specific workstation and also the time requirements due to production constraints. The virtual model is built by using CATIA and DELMIA software by Dassault Systèmes.

The virtual model is used to realize both digital set-ups. The 2D desktop-based simulation set-up uses virtual manikins reproducing the workers' actions. The level of realism is due to the experts' experience in the replication of the human actions by posture sequence. Indeed, manikins are created referring to standard databases (representing a specific population) and considering three different percentiles (i.e., 5p, 50p and 95p). In this set-up, the simulation is carried out within a digital environment and human postures are simulated after a careful observation of real workers, when available, or a detailed description of workstation and task execution by involving production engineers. Creation of all postures is usually time consuming and requires reliable information to have a realistic simulated postures.

The 3D MR immersive simulation set-up is created using the workstation 3D model and displaying it within a VR-based immersive environment for immersive. The main elements characterising human interaction (e.g., work desk, handled tools) are replicated by rapid prototyping using 3D printing and put into the scene. 3D active glasses allow superimposing the stereoscopic viewing with real objects. Within such environment, real users execute the required tasks and a full-body motion capture allows replicating their actions and moving them into a virtual manikin. The obtained manikin is now inserted into the virtual scene and used also for ergonomic assessment by DHM software. The specific set-up realized is based on a Steward large screen for rear projection (6x2 meters), two high-performance Barco Galaxy NW-7 projectors, active stereo glasses with active Volfoni Edge RF, a Vicon optical tracking system with eight Bonita cameras; a Denon AVR sound system with Dolby surround. The virtual model is built by using DELMIA software by Dassault Systèmes and the human manikins are rebuilt into the virtual scene by using RTI DELMIA plug-in by Haption. In the study passive markers are used for motion capture. A set of ad-hoc rigid bodies has been realized by 3D printing for a precise full-body motion capture. Figure 2 shows the mixed reality set-up realized for digital simulations. It presents the mixed reality environment, the motion capture layout by eight Vicon cameras, and the real user motion capture by rigid bodies equipped with passive markers. Figure 3 shows an example of simulation within the MR simulation set-up.

The main advantages of the MR simulation set-up are: the possibility to have a more realistic replication of the workers' action into the virtual scene, due to the motion capture; the higher level of immersion for the users; the higher simplicity for simulation creation; the lack of direct observation of workers at the shop floor or the involvement of production engineers to generate reliable simulations; the possibility to carry out interviews to users' during task execution within the simulation environment.

Figure 2. The mixed reality simulation set-up for human-centred immersive simulation: the mixed reality environment (A), the motion capture layout (B), and the full-body motion capture of the real user (C)

Figure 3. Example of simulation within the mixed reality simulation set-up

4. Industrial case study

4.1 Case study description

The industrial case study has been developed in collaboration with Tenaris SA (http://www.tenaris.com), 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. The defined protocol has been adopted to identify the main criticalities in terms of physical and cognitive workload and to support the definition of re-design guidelines. Such a workstation has been selected for this study due to its presence in all Tenaris 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.

Figure 4 shows the four tasks simulated during the case study for the selected workstation: pipe external and internal grinding, pipe internal cleaning, and pipe ovalization control. The external grinding consists of grinding the defects on the external surface of the pipe by using a grinder that is manually handled by the worker. The internal grinding 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. The 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. Finally, ovalization control 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.

Figure 4. Tasks simulated during the case study for the selected workstation

4.2 Task simulation

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. The specific actions and the parameters considered for each simulated task are described in Table 5. The four tasks were analysed by three different modalities: a) traditional ergonomics study by workers' observation and experts' heuristic evaluation by checklists, b) digitizing the workspace and adopting the desktop-based simulation set-up using virtual manikins, which postures were inferred from workers' video recording and interviews, and c) creating a mixed reality immersive set-up where tasks were simulated by real users interacting with real and virtual objects, as described in section 3.3. In all cases, the proposed protocol was adopted for the human workload assessment.

Table 7. Task simulation for the case study

Task	Activities	Variable parameters	Fixed parameters
1. Pipe external grinding	1. Grinder grabbing 2. Grinder positioning on the pipe 3. Manual grinding	1. Pipe diameter D (400 – 700 mm) 2. Working plane height H (400 – 800 mm)	Grinder weight: 6,5 kg Frequency: every 10 minutes approx.
2. Pipe internal grinding	1. Grinder grabbing 2. Grinder positioning into the pipe 3. Grinder hoking with the carriage 4. Grinding by moving the carriage 5. Grinder removing out of the pipe	1. Pipe diameter D (400 – 700 mm) 2. Working plane height H (400 – 800 mm) 3. Distances from the pipe L (800 – 1000 mm) 4. Handle shape 5. Carriage support height C (1000 – 1400 mm)	Grinder weight: 10 kg Frequency: every 20 minutes approx. Trail length
3. Pipe internal cleaning	1. Compressed air bar grabbing (from the support) 2. Compressed air bar positioning into the pipe 3. Second bar positioning into the pipe 4. Cleaning along the pipe	1. Pipe diameter D (400 – 700 mm) 2. Working plane height H (400 – 800 mm) 3. Bar height B (1000 – 1400 mm)	First bar length: 6 m Second bar length: 4,5 m Maximum pipe length: 16 m Frequency: every 15 minutes approx.
4. Ovalization control	1. Pump grabbing (from the ground) 2. Pump positioning into the sliding guide 3. Grabbing the ovalization control gauge (specific type) 4. Pump insertion into the pipe by using the bar	1. Pipe diameter D (400 – 700 mm) 2. Working plane height H (400 – 800 mm) 3. Bar length B (1600 – 1800 mm)	Pump weight: 10 kg Frequency: every 20 minutes approx.

The first simulation (desktop set-up) was carried out by virtualizing the workstation using CATIA and DELMIA tools, according to the simulation parameters. After that, the DHM module in DELMIA (i.e., DELMIA ERGONOMICS) allowed to create the virtual manikins to perform the ergonomic analysis. Two nationalities (i.e., French and German) and three percentiles (i.e., 5p, 50p and 95p) were considered for simulations. Each task was simulated by a sequence of move to postures (MTPs), made up of more than 20 positions for each tasks to have accurate results. Protocol analysis was carried out by directly using the DHM functions available in DELMIA (e.g., RULA analysis) and by inferring the necessary data by biomechanical analysis data and expert heuristic evaluation on the 3D model. Interviews were carried out by involving users watching the virtual simulation on a large screen desktop and asking the questions about the subjective matters of the protocol. For a more realistic experience, the digital simulation was displayed in the VR-based environment to have a 1:1 scale visualization and user navigation of the virtual environment. No interaction was provided during the simulation. Figure 5 shows an example of the simulation carried out within the desktop set-up for a specific posture of the external grinding.

Figure 5. Simulation of pipe external grinding in digital desktop-based set-up for a specific posture simulation (A), with the analysis of related reach envelope (B) and the head view (C)

The second simulation (MR set-up) was carried out by using the 3D mixed reality immersive simulation set-up described in section 3.3. For each task, the activities were simulated by a real user properly trained by videos of workers in the real workstation. Users moved in the immersive virtual environment and interacted with real and virtual objects during the simulation. The handled devices were reproduced by real objects to create a real interaction feedback. Motion caption and object tracking allowed to virtualize the scene and to create a more reliable virtual simulation. The RTI DELMIA plug-in by HAPTION allowed to track the real object as well as the real user into the virtual scene and to exploit the DELMIA ERGONOMICS tools for same analysis. In this second case, interviews were carried out by involving real users during and after task execution, according to the defined protocol. Figure 6 shows an example of the simulation carried out in the mixed reality set-up for a specific posture of the external grinding.

Figure 6. Simulation of pipe external grinding in immersive mixed reality set-up by involving a real user for two different postures: grinder grabbing (A) and grinding (B)

In both cases, eight users and two experts were involved in the ergonomic assessment. Users were researchers and students observing video recordings of real operators involved in similar tasks on other plants and simulating their actions. Indeed, real operators cannot be involved due to geographical distance and privacy agreements with the company. Experts in human factors and ergonomics evaluated the results according to their experience and the users' feedback.

Both simulations were compared with traditional analysis. Two experts in human factors and ergonomics were involved. Workers were observed during task execution, video recorded and interviewed by experts. Body measures are taken from videos and direct observation; RULA analysis was carried out by RULA checklists, while visibility and accessibility were evaluated by heuristic evaluation. The main difficulties were related to the workers' availability, the intrusiveness of the video recorded especially due to environmental conditions (e.g., lighting, noises), the long monitoring period necessary to collect all the useful information to carry out a compressive analysis, and the huge quantity of information to be processed by experts.

4.3 Results and discussion

The application of the proposed protocol allowed carrying out a detailed analysis of the human workload on the workstation and easily and quickly comparing the results among the different set-ups. Indeed, each task was divided into more than 20 postures (move to postures, MTPs) and physical and cognitive workload was assessed by the protocol metrics. Table 8 shows task analysis for external grinding. All tasks were analysed in the same way. Only 5 MTPs are included for space limit. This simplification was necessary to have a list of "static pictures" (MTPs) where protocol metrics were measured for all set-ups as well as for traditional analysis based on real user observation. Figure 7 shows the comparison between the digital simulation set-ups and the real scene for external grinding. The same comparison was carried out for the other three tasks.

Table 8. Task analysis for external grinding

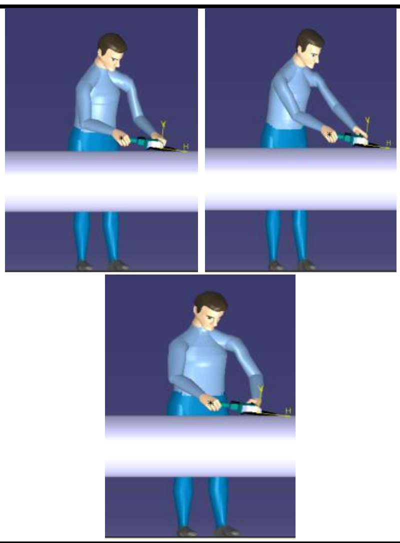
Task analysis by Move To Postures (MTPs)	**Task description**	**Digital representation**
MTP 10	*The worker grabs the grinder from the ground*	
MTP 20	*The worker is approaching to the pipe*	
MTP 30 / 40 / 50	*The worker is grinding the external pipe surface / 1 / 2 / 3*	

Figure 7. Comparison of the simulation set-ups with the real activity for external grinding

The creation of the digital simulation set-ups well supported the analysis of the impact of design features as well as workers' features (e.g. nationality, percentile) on the human performance. Indeed, the virtual scene can be easily changed and the human workload assessed case by case. For this purpose, the protocol well supported the analysis of design alternatives for both physical and cognitive aspects and the definition of the main workstation criticalities to drive its optimization.

For instance, for the analysed workstation, the worst conditions were found with the shortest height of the working plane and for the tallest users, in terms of nationality (i.e., German) and percentile (95p), especially for external grinding and internal grinding tasks. In these conditions, the dis-ergonomic activities are related to grasping / posing objects from / to the ground and for prolonged activities carried out with flexed trunk and extended arms, which causes a high compression force on the back. Similarly, the worst conditions were found also for ovalization control and internal pipe cleaning. The easy way to have digital simulation is by the desktop set-up. Figure 8 summarises the average results obtained for the different conditions under investigation, for the four tasks considered in the case study. Values exceeding the recommended values are marked in red. Figure 9 presents detailed results for one of the worst cases, for external grinding, according to the affecting parameters. Desktop set-up was useful to assess physical workload, even if cognitive workload cannot be assessed. Indeed, sample users' weren't able to express a reliable judgement for the cognitive metrics due to the lack in direct interaction and feedback during task execution.

Figure 8. Simulation results in desktop set-ups for the four tasks analysed (average results)

Figure 9. Experimental detailed results on desktop set-up for external grinding

The same procedure was used to analyse the four tasks also in the mixed reality (MR) set-up and results were compared with data based on real observation. For each metric, data were collected on all samples users according to the protocol analysis as for desktop set-up. In the MR set-up, users were directly involved in task execution tanks to the interaction with physical and virtual objects, and both physical and cognitive assessments were carried out. Figure 10 shows average data collected for the two digital simulation set-ups in the case of external grinding and compares them with data from traditional analysis carried out on real scenes. Only several MTPs are included due to space limits. The table shows the average results for the protocol metrics for two different simulation set-ups (i.e., desktop and MR) and compares them with results collected from traditional analysis carried out on real users observation. Values exceeding the recommended values are marked in red. Figure 11 and Figure 12 compare the results obtained for the task postures (i.e., MTPs) by graphs for RULA and L4-L5 compression force. In the desktop set-up, data were calculated on virtual manikins by DELMIA ERGONOMICS tools. In the MR set-up as well as in traditional assessment, RULA checklist and L4-L5 equations were adopted on the real human data. They differ for the different data source: in the MR set-up data were retrieved by virtualized human manikins after motion capture, while traditional assessment considered human data by users' observation. Similar comparisons were carried out for all tasks and all critical postures and design parameters' combinations.

Figure 10. Experimental results comparison for external grinding

Figure 11. Comparison of the RULA assessment for external grinding in the different set-ups

Figure 12. Comparison of the physical stress assessment for external grinding in the different set-ups

As a result, the main criticalities for each specific task were defined. In particular, experimental results allowed pointing out some interesting findings about simulation effort and accuracy. Firstly, the desktop-based simulation was the simplest one in terms of equipment and users' involved. The analysis was carried out completely in a virtual environment; only a preliminary inspection analysis was necessary to collect all the information to create a reliable simulation set-up. However, the preparation phase involving experts to create the sequence of actions on virtual manikins was time consuming and strongly depends on the experts' subjective analysis of the human postures. Moreover, it could not support interaction and satisfaction analysis. Diversely, the MR set-up supported both physical and cognitive analyses and results were closer to real results on average. It demonstrated that such an environment could well support early assessment during the design stages providing a more accurate response with respect to the desktop set-up. The improved quality of the assessment was due to the direct users' involvements and the motion capture, which allows respectively to collect also subjective responses and to apply physical evaluation on real-based human manikins, not on standardized manikins. Of course, the MR set-up required more expensive hardware and software equipment. Experimentation finally revealed that the combined used of a DHM tool and a virtual environment with the creation of a MR set-up can successfully predict the most critical features of the workstation and support the ergonomic design in a more efficient and proactive way than traditional methods. Moreover, the study demonstrated the importance of combining a structured protocol analysis with experimental tests to evaluate the overall quality of the human-system interaction.

Finally, the analysis of the simulation results in the MR set-up allowed defining some design improvements in order to benefits physical and cognitive ergonomics, in particular:

- in order to limit the physical stress during grinding operations in standing positions (which especially affect back, neck, wrist and arms) on different pipe diameters, the workstation was equipped with a mobile platform to be positioned in the more comfortable position. Indeed, also seating is not proved to be a good way;

- a supporting arm was introduced for internal cleaning and ovalization control, to support the workers' to carry the long bars;
- the workstation design was optimized in some features to improve the visibility during task execution;
- in order to reduce the cognitive workload for the most complex tasks, a summary lists of the operations to be executed could be provided also by mobile interfaces like smartphones and tablets to support the operator to remember the right sequence of actions. Also video and other multimedia material could be provided;
- the satisfaction was proved to be directly connected to the physical and mental workload, so that results demonstrated how reducing both physical and cognitive stress is important to make operators work comfortably and satisfied.

The study had a great industrial impact, since the company could easily identify the main design criticalities of the actual workstation as well as tasks and had a valid support to design the new workstation for its new plants by using virtual prototyping and digital models. The adopted procedure represented a new practice for the company: usually, ergonomics is analysed on real workstations after their creation and only corrective actions are taken.

Obviously, the proposed approach implies also a certain effort for implementation. In particular, the workplaces under assessment have to be digitised and virtualized and a proper testing environment created by involving real users. The experimental study highlighted also the main applicability features of the two proposed set-up in terms of cost, development efforts and effectiveness:

- the desktop-based set-up allows to create a simpler simulation in a quick and easy way and to obtain a useful digital representation by using standard virtual manikins. The simulation is effective to study the workspace layout, define the workers' tasks sequence and provide a general overview of the physical ergonomic performance. Costs and efforts are limited: the main costs are due to the software and the modelling efforts, that can be estimated in few days, depending on the complexity of the workspace to be modelled;

- the MR-based set-up provides a more interactive simulation and offers the possibility to create an hybrid environment by combining virtual and real objects. In this case, real users can be involved, physical ergonomic performances are more accurate and specifically referred to the sample users, and also interaction and cognitive aspects can be evaluated. However, such a simulation requires a higher implementation effort due to a more complex the technological set-up, but it offers more detailed results. Costs are related to motion capture system, digital manufacturing software and the creation of the VR immersive environment. Efforts are related to calibration, modelling, and interfacing between the motion capture systems and the VR environment. Preparation efforts can be estimated in 2-3 weeks depending on the complexity of the workspace to be simulated and tested.

Finally, such an approach can be implemented in different industrial sectors, from energy and gas industry, to automotive or aerospace, until agriculture or machine building for numerous sectors (e.g., packaging, mechanics, food, tissue). It should be considered that the implementation of the proposed approach is easier in those companies where a virtual engineering division already exists, due to the availability of people with the right competences. Usually such companies are middle or large sized. Introduction in small companies is more difficult due to the initial implementation costs and the need of people with the right skills.

5. Conclusions

The paper presents and compares two computer-integrated set-ups to support the design of manufacturing systems with a different level of complexity and interaction provided, based on digital manufacturing. In particular, the research investigates a 2D desktop set-up and a 3D immersive mixed reality set-up, based on digital manufacturing simulation and motion capture, that realizes interaction with both virtual and real objects. An ergonomic analysis on digital workstations was carried out on different tasks by a dedicated protocol, which allows assessing physical and cognitive workload and easily comparing different set-ups. Such a protocol allowed to perform an ergonomic assessment of human tasks and to compare the different digital simulation set-ups with the traditional approach, based on real users' observation. An industrial case study focusing on design optimization of a manufacturing workstation for energy industry is used to test the set-up effectiveness to support re-design actions and to valuably compare the thee digital set-ups with the traditional practices. Workers' tasks and positions as well as their cognitive reactions during task execution were simulated and analysed thanks to the involvement of experts in ergonomics and human factors and workers from the company. Experimental results demonstrated how a mixed reality set-up could improve the ergonomic assessment quality on digital models and limited the simulation efforts with respect to desktop simulations, to achieve results close to traditional assessment on real works. Such a set-up also allowed to define a set of preventive actions from the design process and to validate different alternatives by considering the impact of the design parameters (i.e., dimensional data) and workers' anthropometrical features. In particular, the use of a 3D virtual immersive environment allowed users visualizing the workstation in a 1:1 scale and reproducing real actions on mixed environment, adding cognitive analysis. This fact allowed better detecting problems and finding out solutions from the early design stages. The study finally discussed the limitations and benefits of the different simulation set-ups and demonstrated the importance of combining a structured protocol analysis with tests on virtual workstations, where both physical and cognitive performances can be assessed to measure the human-system interaction.

Future works will be focused on the improvement of the MR set-up with the analysis of the workers' feedback by biometrical parameter's monitoring (e.g., hearth rate, electro-encephalography, eye tracking) in order to support the analysis of both psychical and cognitive stress, and to enhance the simulation by haptic devices, to add realism to the virtual simulation and reduce the real objected used in the MR set-up, reducing preparation time and cost.

References

Adler, P.S., Goldoftas, B. and Levine, D.I.: "Ergonomics, employee involvement, and the Toyota production system: A case study of Nummi's 1993 model introduction", Industrial & Labor Relations Review, Vol. 50 (3), 1997, pp. 416-437.

Berg, L.P. and Vance, J.M.: "Industry use of virtual reality in product design and manufacturing: a survey", Virtual Reality, Vol. 21 (1), 2017, pp-1-17.

Broberg, O., Fallentin, N., Hasle, P., Jensen, P.L., Kabel, A., Larsen, M.E. and Weller, T.: Human Factors In Organizational Design And Management, IEA Press, Santa Monica CA, USA, 2014.

Buckle, P. and J. Devereux: "Work Related Neck and Upper Limb Musculoskeletal Disorders", European Agency for Safety and Health at Work, Luxembourg, 1999, pp. 7-8.

Chaffin, D.B.: "Human motion simulation for vehicle and workplace design", Human Factors and Ergonomics in Manufacturing, Vol.17, No.5, 2017, pp. 475-484.

Chen, J., Mitrouchev, P., Coquillart, S. and Quaine, F.: "Disassembly task evaluation by muscle fatigue estimation in a virtual reality environment", Int. J. Adv. Manuf. Technol., Vol. 88 (2017) pp. 1523–1533.

Demirel, H.O. and Duffy, V.G.: "Applications of digital human modeling in industry", V.G. Duffy (Ed.) Digital human modeling, HCII 2007, LNCS 4561, Berlin, Heidelberg, Springer, 2007, pp. 824-832.

Dempsey, P.G.: "Usability of the revised NIOSH lifting equation", Ergonomics, Vol. 45 (12), 2002, pp. 817-828.

Dos Santos, Z.G., Vieria, L. and Albinotti, G.: "Lean Manufacturing and ergonomic working conditions in the automotive industry", Procedia Manufacturing, Vol. 3, 2015, pp. 5947 – 5954.

Dul, J. and Neumann, P.: "Ergonomics contributions to company strategies", Applied Ergonomics, Vol.40, 2009, pp. 745-752.

Enomoto, A., Yamamoto, N. and Suzuki, T.: "Automatic estimation of the ergonomics parameters of assembly operations," CIRP Ann. - Manuf. Technol., vol. 62 (1), 2013, pp.13-16.

Gavish, N., Gutiérrez, T., Webel, S., Rodríguez, J., Peveri, M., Bockholt, U. and Tecchia ,F.: "Evaluating Virtual Reality and Augmented Reality Training for Industrial Maintenance and Assembly Tasks", Interact. Learn. Environ. Vol .23 (6) (2015) pp. 778-798.

Gonzalez-Badillo, G., Medellin-Castillo, H. and Lim, T.: "The development of a physics and constraint-based haptic virtual assembly system", Assem Autom, Vol. 34 (2014) pp. 41-55.

Grajewski, D., Górski, F., Zawadzki, P. and Hamrol, A.: "Application of Virtual Reality Techniques in Design of Ergonomic Manufacturing Workplaces", Procedia Comput. Sci., Vol. 25 (2013) pp. 289-301.

Hendrick, H.W.: "Applying ergonomics to systems: some documented "lessons learned"", Applied Ergonomics, Vol.39, 2008, pp. 418-426.

Hignett, S. and McAtamney, L.: "Rapid entire body assessment (REBA)", Applied Ergonomics, Vol. 31 (2), 2000, pp. 201-205.

Hu, B., L. Ma, W. Zhang, G. Salvendy, D. Chablat, F. Bennis: "Predicting real-world ergonomic measurements by simulation in a virtual environment", International Journal of Industrial Ergonomics, Vol.41, 2011, pp.64-71.

Hwang, S.L., Yau, Y.J., Lin, Y.T., Chen, J.H., Huang, T.H., Yenn, T.C. and Hsu, C.C.: "Predicting work performance in nuclear power plants", Safety Science, Vol. 46, 2008, pp. 1115-1124.

Kalviainen, M.: "Product design for consumers taste", Green W.S. and Jordan P.W. (Eds) Pleasure with products: beyond usability, Taylor & Francis, London, 2002, pp. 77-96.

Karhu, O., Harkonen, R., Sorvali, P. and Vepsalainen, P.: "Observing working posture in industry: Examples of OWAS application", Applied Ergonomics, Vol. 12, 1981, pp. 13-17.

Kim, K.H., Martin, B.J., Chaffin, D.B.: "Modelling of shoulder and torso perception of effort in manual transfer tasks, Ergonomics, Vol. 47 (9), 2014, pp. 927-944.

ISO 9241-210, Ergonomics of human system interaction - Part 210: Human-centered design for interactive systems, International Organization for Standardization (ISO), 2009.

Lawson, G., Salanitri, D. and Waterfield, B.: "Future directions for the development of virtual reality within an automotive manufacturer", Appl. Ergon. Vol. 53 (part B), 2016, pp. 323-330.

Li, G. and Buckle, P.: "Current techniques for assessing physical exposure to work- related musculoskeletal risks, with emphasis on posture-based methods", Ergonomics, Vol.42 (5), 1999, pp. 674-695.

Lin, C.L., Wang, M.J.J., Drury, C.G., Chen, Y.S.: "Evaluation of perceived discomfort in repetitive arm reaching and holding tasks", International Journal of Industrial Ergonomics, Vol. 40 (1), 2010, pp. 90-96.

Marzano A., Friel I., Erkoyuncu J.A. and Court S.: "Design of a virtual reality framework for maintainability and assemblability test of complex systems", Procedia CIRP, Vol. 37 (2015), pp. 242-247.

Maudgalya, T., Genaidy, A. and Shell, R.: "Productivity-quality-cost-safety: a sustained approach to competitive advantage e a systematic review of the National Safety Council's case studies in safety and productivity", Human Factors and Ergonomics in Manufacturing, Vol.18 (2), 2008, pp. 152-179.

McAtamney, L. and Corlett, E.N.: "RULA: a survey method for the investigation of work-related upper limb disorders", Applied Ergonomics, Vol. 24 (2), 1993, pp. 91-99.

Mengoni, M., M. Peruzzini, F. Mandorli, M. Bordegoni, G. Caruso: "Performing ergonomic analysis in virtual environments: a structured protocol to assess humans interaction", Proc. 28th ASME IDETC/CIE International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Part A&B, Vol.3, 2008, pp. 1461-1472.

Norman, D.A.: The Design of Everyday Things, New York, Doubleday, 2008.

Nunes, I.L.: "FAST ERGO_X – a tool for ergonomic auditing and work-related musculoskeletal disorders prevention", WORK: A Journal of Prevention, Assessment, & Rehabilitation, Vol. 34 (2), 2009, pp. 133-148.

Nunes, I.L., and McCauley Bush, P: "Work-Related Musculoskeletal Disorders Assessment and Prevention", Ergonomics – A Systems Approach,.Nunes I.L. Ed., CC BY.

Nunes, I.L.: "Integration of Ergonomics and Lean Six Sigma: A model proposal", Procedia Manufacturing, Vol 3, 2015, pp. 890 – 897.

NRCIM, National Research Council and Institute of Medicine: "Musculoskeletal Disorders and the Workplaced Low Back and Upper Extremities", National Research Council and Institute of Medicine, Washington, 2001.

Occhipinti, E. and Colombini, D.: "A toolkit for the analysis of biomechanical overload and prevention of WSMDs: Criteria, procedures and tool selection in a step-by-step approach", Ind. J Industrial Ergonomics, Vol.52, 2016, pp.18-28.

Perry, C.M., Sheik-Nainar, M.A., Segall, N., Ma R. and Kaber, D.B.: "Effects of physical workload on cognitive task performance and situation awareness", Theoretical Issues in Ergonomics Science, Vol. 9, 2008, pp. 95-113.

Rahman, M.N.A., Rani, M.R.A. and Rohani, M.J.: "WERA: An Observational Tool Develop to Assess the Physical Risk Factor associated with WRMDs", Journal of Human Ergology, Vol. 40 (2), 2011, pp. 19-36.

Rahman, M. L.: "Study and analysis of work postures of workers working in a ceramic industry through rapid upper limb assessment (RULA)", International Journal of Engineering and Applied Sciences, Vol. 5 (3), 2014, pp. 14-20.

Salvendy, G. and Karwowski, W.: "Advances in Cognitive Ergonomics", Advances in Human Factors and Ergonomics Series, CRC Press, Taylor & Francis, 2010.

Sluiter, J.K.: "High-demand jobs: age-related diversity in work ability?", Applied Ergonomics, Vol. 37, 2006, pp. 429-440.

Sundin, A. and R. Ortengren: "Digital human modeling for CAE applications", G. Salvendy (Ed.), Handbook of human factors and ergonomics, Hoboken, NJ: John Wiley & Sons, pp.1053-1078, 2006.

Wang, X., Ong S.K. and Nee A.Y.C.: "Real-virtual components interaction for assembly simulation and planning", Robot. Comput. Integr. Manuf. Vol. 41 (C) (2016) pp.102-114.

Wilson, J.R.: "Fundamentals of ergonomics in theory and practice", Applied Ergonomics, Vol.31, 2000, pp. 557-567.

Young, M.S. and Stanton, N.A.: Mental Workload. In N. A. Stanton, A. Hedge, K. Brookhuis and E. Salas (eds.), Handbook of Human Factors and Ergonomics Methods, Taylor and Francis Group, London, 2004.