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Integrating mocap system and immersive reality for efficient human-centred workstation design

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Abstract: The paper presents the VR-Ergo Log system, an inertial motion capture system integrated with immersive reality and combined with a heart rate monitoring. By using immersive reality, the operator will be able to move and interact within a virtual workplace environment, in order to permit a fast and efficient ergonomic assessment of future workplace solutions and to avoid all cost-consuming activities related to the pre-production design of the workplace or to the prototyping of new products. This integrated system allows to evaluate in advance the time-based and ergo-based indices which can help the practitioners on understanding how to design the workplace and the devices to be used by operators. In addition, the use of the heart rate monitor permits to have a real-time feedback regarding the fatigue the operator is perceiving. The use of such a system will help to make more efficient the early design phases of an industrial workspace, by also considering the impact of human diversity and avoiding non-ergonomic solutions especially when an ageing workforce will be enrolled in the system.

Keywords: motion capture system, virtual reality, ergonomics, human-centred workspace, ageing workers

1. INTRODUCTION

Considering the important need of producing innovative product models and increasing the product variety, future production will be required to become always more flexible (Cavatorta and Dipardo, 2009). Moreover, Europe is facing the development of an inverted population pyramid, with a consequent deep ageing phenomenon of the workforce (Gonzalez and Morer, 2016). Such changes inevitably require the study of strategies, as well as adaptable tools and devices, to properly involve older workers in industrial processes (EC, 2010).

Accordingly, the future trend is to design changeable production and assembly systems, which can give the possibility to vary their layout and configuration, depending on the kind of product to be produced and on the kind of worker that will work in it, by taking into account the human diversity factors (gender, age, body measures, physical capabilities). This permits them to become not only customer-oriented (Cavatorta and Dipardo, 2009) but also user-oriented, fostering the employment of all the operators, regardless their physical characteristics (Garbie, 2014).

Consequently, the performance of the production systems is strongly connected to the operators' performance, influenced by their personal skills in performing the specific task and by the ergonomic conditions of the workplace (Brinzer and Banerjee, 2018). Thus, to reach the improvement of the performance, the production system needs to be work-oriented designed for assuring the minimization of operators' fatigue and awkward postures. In relation to this and considering the personal characteristics which distinguish one operator from the other, a production system should also be able to adapt to the operator who has to perform the activity and to support him in the best way during the performance of the task (Cimino et al., 2009).

From this it derives the need of understanding and defining in advance the workstation characteristics for assuring productivity, operator's well-being, safety and product quality (Peruzzini et al., 2017). Usually, companies devote a part of the production area for the creation of workstations prototypes, in which it can be evaluated the interaction modalities of the operator with the workplace. Furthermore, these workstation prototypes are used to train operators. This imply several costs which the company has to sustain, for example production or purchase costs of the prototypes, space usage costs and staff costs.

The aim of this paper is to present a system which can solve the problems related to the design of human-centred workstations. This system, called VR-Ergo Log system, consists in the integration of a motion capture system with an immersive reality device and a heart rate monitoring system. The use of such a system permits to test a workstation without having built it physically in advance, by immersing the operator into a virtual environment. Moreover, it is possible to perform in real time an ergonomic analysis with the use of a motion capture system integrated with a specific ergonomic assessment software (as reported in Battini et al., 2014) and to evaluate the level of fatigue of the operator by monitoring his heart rate (Calzavara et al., 2017). By using this system, the operator can also be virtual-trained before performing the activity in the real production system, giving immediate feedbacks related to the workstation design. The virtual training could also concern new products or models which are

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still in a pre-production phase, or it could involve ageing and expert workers in the training of the younger and less expert ones, in order to avoid wrong and non-ergonomic movements and procedures. Moreover, it could be possible to obtain the operational characteristics of the workstation and to adapt it to the personal characteristics of the operators (e.g height, age, experience on the task to be performed, training status, way in which the operators usually moves the body).

The remainder of the paper is organized as follows. In Section 2 it will be explained the existing literature focused on motion capture systems and virtual reality. Then, Section 3 and 4 present the characteristics of the VR-Ergo Log system and its possible applications, respectively. Finally, in Section 5 some conclusions and some suggestions for future researches are defined.

2. MOTION CAPTURING AND VIRTUAL REALITY

Workplace design and ergonomics are strictly related. This is due to the influence of repetitive movements and awkward postures, which the operator experiences during the performance of the activity, on the development of musculoskeletal disorders. Understanding this link, recent literature has been focused on the development of a framework able to take into account both the technological aspects and the environmental and workforce ones during the pre-production design of an assembly system (Battini et al., 2011). For evaluating awkward postures of operators, there exist different ergonomic assessment methods which usually are classified in self-reports, observational methods and direct measurements (David, 2005). For performing a complete ergonomic analysis, usually it is necessary to jointly apply more than one ergonomic method. In relation to this, the most used ones are OWAS, RULA, REBA, LUBA, OCRA, NIOSH, BORG SCALE and Strain Index (Battini et al., 2014; Otto and Battaia, 2017; Otto et al., 2017).

As far as ergonomic analysis is concerned, recent literature has presented innovative systems that permit to have real-time ergonomic assessment in an industrial context (Vignais et al, 2013; Battini et al., 2014; Vignais et al., 2017). In Vignais et al. (2013) the benefits of using an inertial motion capture system (mocap), based on a network of inertial measurements units placed on the upper part of the body and connected one with the other, are put in evidence. In fact, by using this system it is possible to evaluate different kinds of movements of the operator by computing the RULA index in real-time and by giving a simultaneous feedback to the operator. The application of this system has been further developed in Battini et al. (2014), where an inertial motion capture system is applied for evaluating manual material handling activities where the whole body is involved. In addition, specific tools have been developed, not only for an ergonomic analysis of the whole body but also for the evaluation of the kind of task, of the time and of the methods used to perform the activity. Despite the recent development of systems based on optical sensors rather than inertial ones (Puthenveetil et al., 2015), a motion capture system based on inertial sensors would be preferable since it does not need a camera and it is more precise in detecting the movements. In Faccio et al. (2017) it is introduced a Motion Analysis System (MAS) where the inertial and optical mocap are integrated and a new ergonomic index based on ISO 11226 and EN 1005-4 is introduced. Moreover, other researches have considered to reproduce the movements captured with such systems in virtual environments by using ad hoc software (Liu et al., 2015). These innovative systems permit to have suggestions for the redesign of the workstation by improving the ergonomic aspects (Vignais et al., 2017) but, by themselves, they do not permit to make evaluations during the pre-production design of the workstations. If fact, they do not allow to simulate the tasks the operator has to perform in the real production system.

This limitation can be overcome by using virtual reality (VR), which is defined as the set of technologies that permit people to experience in an immersive way a world beyond reality (Berg and Vance, 2017). The virtual reality can be reproduced in different ways, by using projection screens or head mounted displays (HMD). The employ of VR is interesting since it can be applied in advance during the design process but also for addressing issues that emerge during the operation of the system (Berg and Vance, 2017). Till now, VR has found various applications in production systems (Lawson et al., 2016). First of all, it can be used for designing, virtual prototyping and manufacturing products, since it permits to replicate the real models and to avoid the need of creating a physical mock-up and to physically reproduce the manufacturing processes. In addition, it can be useful for simulating the assembly and disassembly of objects with the creation of virtual workspaces and to improve the training of operators in comparison to real equipment. As far as the design of workplaces is concerned, the VR allows to make considerations regarding the adjustments of the devices or machines to be used by the operator or regarding the organization of the workplace (Grajewski, 2013). VR can also be applied for training in several disciplines by creating interactive virtual environments: military training, virtual emergency evacuation, virtual firefighting (Kwon et al., 2017). Moreover, its usage has also been acknowledged for the training of operators in assembly and maintenance tasks (Gavish et al, 2015) and its effectiveness has been recognised particularly when real activities are too expensive or present some characteristics that make them almost impossible to be performed in practice (Grajewski et al, 2015).

Recently, the integration of virtual reality with motion capture systems (optical or inertial) is gaining a lot of interest and applications. Table 1 reports some of the contributions that have been proposed in this sense. Some of these researches, for example, have tried to evaluate a system based on an optical motion capture integrated with virtual reality (Chagué and Charbonnier, 2016; Podkosova et al., 2016; Rincon et al., 2016). However, the use of this system does not permit to have precision in capturing the movements of the operator performing a task and no ergonomic analysis is carried on in real-time during the performance. In Peruzzini et al. (2017) the human-centred design of the workplace is obtained by carrying on two simulations in sequence. The first one is performed by using Delmia V5-6R2016, digitalizing the operator and the workstation layout in a software environment. The second one is obtained by replicating the activities with real operators in a virtual environment tracking the movements with an optical motion capture system. These two steps of simulation are followed also in Caputo et al. (2017), where the VR system aims at validating the results of the software simulation with the physical simulation before performing the EAWS checklist assessment. These two-steps simulation is overcome in Vosniakos et al. (2017), where the data of Oculus HMD for VR and the ones from Kinect II Sensor for motion records are combined to perform the ergonomic analysis.

Table 1. Comparison of existing contributions on the integration of motion capture system and VR

	Motion capture	VR	Ergonomics analysis	Description	Differences with VR-Ergo Log
Chagué and Charbonnier (2016)	Optical	✓		Combination of motion capture with VR headsets: users can freely move within the physical space while virtually visiting a virtual world and interacting with 3D objects or other users using the sense of touch.	- Optical motion capture - Lack of ergonomic analysis
Podkosova et al. (2016)	Optical	✓		An optical head tracking is coupled with a low-cost motion capture suit to track the full body and the head.	- Optical motion capture - Lack of ergonomic analysis
Rincon et al. (2016)	Optical	✓		Creation of an immersive videogame that integrates motion capture, electromyography (EMG) sensing and VR in one unique system using Unity engine and the design of EMG sensors.	- Optical motion capture - Use of EMG for controlling muscle contraction
Peruzzini et al. (2017)	Optical	✓	✓	Creation of an immersive simulation environment adopting virtual reality and mixed prototyping, merging real and virtual objects, to optimize the physical ergonomics in workstation design.	- Optical motion capture
Vosniakos et al. (2017)	Optical	✓	✓	Application of virtual reality for assessing human-based assembly of large mechanical parts	- Optical motion capture
Caputo et al. (2018)	Inertial	✓	✓	Simulation with Siemens Tecnomatix™ software for ergonomic assessment. Then validation in a virtual workstation.	- Ergonomic analysis in parallel with the use of virtual reality

The aim of the following Sections is to present the VR-Ergo Log system. Here, virtual reality is obtained with a head mounted display (HMD), which is combined with an inertial motion capture system which guarantees the precision in the tracking of the movements. The VR is used for immersing the operator in an environment which reproduces a reality under study, in which he can perform the real activities. This permits to have a real-time feedback regarding the kind of movements the operator is doing. Consequently, it can be of help in the setting of the specifications for the design and the usage of the station before its realization. In addition, the training of existing operators in relation to new products or the training of new operators can be improved and performed without physically reproducing the workstation.

3. CHARACTERISTICS OF VR-ERGO LOG SYSTEM

The new VR-Ergo Log system is based on an inertial motion capture system, developed by Synertial (UK), connected to Siemens Jack™ software (Siemens, 2017) for reproducing the movements into the virtual environment and on VIVE™ system (Vive, 2017) for virtual reality. Figure 1 shows the developed system, together with the software environment. The system includes also a heart rate monitor, for the analysis of the physical fatigue perceived by the operator during fast and repetitive movements and during walking or moving (Strath et al., 2000). Moreover, it is possible to give a load to the operator during its virtual activities, in order to evaluate the impact of the handling of an item of a certain weight on fatigue level and on ergonomics. Of course, the same result could be obtained with different devices and technologies. In this case, the choice of this configuration is due to the previous availability of the inertial motion capture system (Battini et al., 2014) and to its previous integration with Siemens Jack™ software.

The VR-Ergo Log system is composed of:

• *Inertial motion capture system*. The system consists of 31 inertial measurement units (IMUs) placed on a full body suit, including the hands. All the sensors communicate with a small portable multi-processing unit (MPU), which sends the data to a personal computer through Wi-Fi connection (for further explanation see Battini et al., 2014). The data collected concern the whole body in terms of body joint angles, body segment orientation and positions.

• *VIVE™ system*. The HTC VIVE™ system, developed by HTC and Valve corporation, is a virtual reality headset, composed of a head-mounted display, two wireless handheld controllers and two 'Lighthouse' base stations, emitting pulsed IR lasers (Vive, 2017). It permits the user to move in a 3D environment and to interact with the environment by using motion tracked handheld controllers. The VIVE™ system has two screens, one for each eye with a resolution of 1080x1200. Moreover, the headset and the controllers have 70 infrared sensors, a gyroscope and an accelerometer. The movements of the operator are tracked with millimetre precision by using these sensors and the two 'Lighthouse' base stations. The operating system is SteamVR, running on Microsoft Windows. The VIVE™ system is connected to the computer through a USB cable.

• *Heart rate (HR) monitoring system*. The HR monitor used, called Polar V800, is based on a Bluetooth HR sensor connected to a watch. This device is easy to use, to understand and gives real-time feedback to the operator regarding his physical condition in relation to the cardio-vascular system. In fact, with this device the heart rate of the operator is monitored second by second during the performance of the activity.

• *Software tool for time-based and ergo-based analyses*. The data collected with the inertial motion capture system are processed by a real time software tool developed in Battini et al. (2014). This software permits to have an ergonomic assessment in real-time using RULA, OWAS, OCRA and Lifting Index methods. In addition, it is possible to evaluate other indices related to the position of the hands and to the horizontal and vertical movements of the hips. These indices are used for estimating the percentage of time spent by the hands at different heights and to estimate the distance covered during the performance of the activity, indicating when the operator is kneeling or lowering. Moreover, simulation software permits the virtual human prototyping in the virtual environment of the software performing an ergonomic assessment.

As already explained, the VR-Ergo Log system for now allows to consider the fatigue due to the handling of heavy objects only through a real handling by the operator. In the future, it could be considered to integrate the EMG activity in the system, so that to understand if the user is exerting sufficient force in relation to the weight to be lifted or generally to the activity to be performed (Chen et al., 2015). In fact, the EMG electrodes placed on the forearms and arms give the information to the computer, which causes the motion of the virtual object according to how much the user is contracting the muscles (Chen et al., 2015). In this way, it would be possible to carry on also virtual exertions.

This integrated system permits to calculate all the KPIs related to ergonomics, to the performance of the operator in terms of time and to the fatigue the operator is perceiving during and after the performance of different activities.

4. SYSTEM USE: INPUT AND OUTPUT DATA

The employ of the VR-Ergo Log system could lead to interesting advantages from a concurrent engineering perspective. The practical use of the system consists in creating a virtual environment, in which the operator is expected to work. Such environment, developed in typical simulation software and integrated with the VIVE™ system, should reflect one or even more possible configurations of the workstation under study. The human operator, by wearing the motion capture suite and the VR headset, is immersed in that virtual reality. Therefore, he can virtually perform all the activities that he normally would do during his job, but without needing a physical prototype of the workstation.

Fig. 1. VR-Ergo Log system.

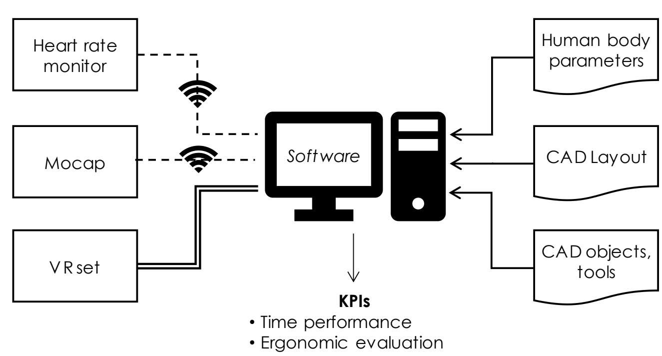

Fig. 2. Scheme of the VR-Ergo Log system.

Figure 2 shows a scheme of the whole VR-Ergo Log system, showing the relations among the various parts and the input/output data. The data collected by the system during the virtual execution of the tasks are useful to evaluate the goodness and the effectiveness of a certain configuration of a workplace under study. This can be done through the determination of a set of specific indicators (KPIs), referring to time, ergonomics and fatigue performance. This would allow to have a real-time feedback inherent to possible changes that have to be done for improving the performance of the operator in the workstation (e.g. moving objects and relocating products). In fact, as already pointed out in previous researches (Battini et al. 2011), during the workplace design phase it is necessary to include not only the technological variables related to the market demand, to the product and to the assembly process but also the environmental variables. These variables are linked to the physiological and psychological wellbeing of the workforce.

In the following, it is proposed a tentative list of time, ergonomics and fatigue based indices which can be obtained through the employ of the VR-Ergo Log system. Of course, this is not a comprehensive list of all the possible indicators which can be calculated from the output data and that could be considered for the redesign of a workstation. Furthermore, they could also differ according to the working environment and/or to the problem under study.

For example, some KPIs regarding time-performance could be: the total time necessary for performing a specific task; the percentage of time the operator requires for the performance of the value-added activities rather than the non-value-added activities (i.e. picking activities); the percentage of time the operator spends in the golden zone, defined as the area closest to the worker's body, between the waist and the shoulders: more time the operator is in the golden zone more time it is avoided the need of stretching or bending, which can imply serious ergonomic problems. Other ones are: the percentage of time the operator stays in an upright position, indicating how much the operator is employed, during the performance of the task, for kneeling or lowering; the time the operator needs for moving into the workstation, obtained from the horizontal movements of the hips; the percentage of picking errors related to a specific workplace design.

On the other side, for the ergonomic evaluation it could be interesting to estimate in real time the value of RULA, OCRA, OWAS and Lifting Index thanks to the tools developed in Battini et al. (2014). By recording this data, it is also possible to estimate the percentage of time the operator spends at a high value of these indices, then with a negative impact on ergonomics.

Furthermore, through the integration of a heart rate monitor in the system, some indices regarding fatigue level and performance can be evaluated: average HR, useful to indicate the mean energy expenditure rate of an activity for the specific operator (Ceesay et al., 1989); the influence of each task on the fatigue accumulation of the operator, measured through an HR increase (for example due to a high weight to be lifted); the influence of erroneous postures on the fatigue perceived by the operator, measured through an HR increase (awkward postures can increase HR, and a fatigued operator could perform the activity in a wrong way); the needed recovery time, estimated by monitoring the fatigue level; the impact of fatigue on tasks duration, so an increase of the fatigue level can affect the time necessary for performing a task.

The possibility of having an overall view of the impact of a certain workplace setting on the operators using these KPIs, can be of help for defining the priorities of intervention and to understand when (and how) the workstation is ready to be realized in practice. Therefore, the virtual workplace can be modified according to these criticalities and immediately verified with the use of the system. The comparison of the indices permits to estimate the best workplace configuration before it has been really built.

5. CONCLUSIONS

In this paper the VR-Ergo Log system, consisting in the integration of a motion capture system with an immersive reality device and a heart rate monitoring system, has been presented. An operator wearing this system is immersed and can effectively act in a virtual environment, which has been properly set up in order to evaluate a possible future real workplace configuration. Thanks to its characteristics, this system gives several advantages in the pre-production design of a workstation, avoiding the need of creating a physical prototype of the workstation or of the product to be assembled, and in the effective training of the operators. This integrated system permits to have a complete vision, in a short time, of how a predetermined design impacts on different aspects: tasks execution time, ergonomics and fatigue. Moreover, there is the interesting advantage related to costs savings, which can be obtained by anticipating the design of the working environment and the training of workers. However, it has to be pointed out that the use of this system can have a certain influence on operators. In fact, the use of the motion capture suit and of the virtual reality might affect the cognitive aspects of the operator, who can feel, at the beginning, a little disoriented. In addition, the operator may experience vision problems due to tiredness when wearing the VR glasses for a too long time. It is therefore important to consider an effective employ of such a device and to allow proper rests during testing. Future researches on this topic will concern the practical use of this system in real case studies. A proper validation of the system could be done, at first, by comparing the virtual environment with a real setting. In addition, such an application could show more insights on the results that can be obtained, both in terms of productivity and of ergonomic improvement.

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