A Preventive Ergonomic Approach Based on Virtual and Immersive Reality

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Abstract. The introduction of new information and communication technologies (ICT) in factory environment is leading the world of manufacturing industry to a change. Indeed, we talk about Industry 4.0, the fourth industrial revolution, that facilitates the vision of a Smart Factory in which systems become cyber-physical, interact between themselves, monitor and validate physical processes, creating a virtual copy of the physical world and making decisions based on complex numerical analysis. Virtualization and simulation of production processes generate several benefits, in terms of costs and time, optimizing the assembly line design and studying human-machine interaction. Regarding the last topic, this paper proposes an innovative method for ergonomic analysis of workplaces on automotive assembly lines in a virtual environment. The method can represent an innovation for human-centered design of workplace in developing new products, reducing costs and improving job quality thanks to a preventive ergonomic approach.

Keywords: Virtual ergonomics · EAWS · Human-centered design · Virtual simulation · Motion capture system

1 Introduction

The world of manufacturing industry, during the last years, is knowing a period of changes, thanks to the increasing use of new technologies in the factory. It can be seen as a new industrial revolution, from which the name Industry 4.0.

Industry 4.0 proposes the realization of smart factories in which systems become cyber-physical and can interact between themselves, simulating the real world in a virtual scenario and making decision based on numerical analysis.

In this way, factories have chance to become more flexible and collaborative, in order to satisfy the current demands of an increasingly competitive market.

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The main characteristics of this new industrial paradigm is the use of PLM (Product Lifecycle Management) software that allows to manage the whole lifecycle of products and processes, generating several benefits, principally in designing manual workplaces and defining cycle time, based on a human-centered approach.

Modern factories cannot ignore the continuous development of virtual reality software. For this reason, an important aspect of Industry 4.0 is represented by Digital Manufacturing (DM), the industrial declination of virtual reality, that integrate a wide set of technologies to support the production, from the design to the product realization, monitoring and optimizing the production processes.

From an ergonomic point of view, these aspects give the opportunity to create manual workplaces in a virtual scenario, where it is possible to simulate manual tasks and evaluate ergonomic indexes, according to which they are designed.

In Fiat Chrysler Automobiles (FCA) factories a preventive ergonomic approach in designing new workplaces has been developed during the last years: Ergo-UAS method. This method is applied during both Process/Product Design and Process Industrialization and it is composed by EAWS (European Assembly Work Sheet) and UAS (Universal Analyzing System). EAWS [18] is a first level ergonomic screening for the evaluation of biomechanical overload risk. The UAS is a typical example of MTM (Method-Time-Measurement) system which is used for the definition of times and methods of work, describing the sequence of operations of a specific work task, assigning a predetermined standard time from the direct observation of the worker and the nature of the movements during the given task.

In order to achieve these results, a lot of information, principally related to human factors, are necessary to satisfy mandatory ergonomic standards. In fact, at FCA Mirafiori Plant, it has been established an ergonomics laboratory, called *ErgoLab*, where many physical parameters concerning the assembly tasks can be investigated, reproducing a real workplace, with a real Body in White car, in which manual tasks are carried on. The main analysis conducted concern postural aspects and effort exerted by the workers by means of innovative tools [1].

To prove the effectiveness of the proposed strategy and to compare simulation results with real experimental data, a modular motion tracking system, based on inertial sensors [2], has been developed at the Dept. of Industrial and Information Engineering of the University of Campania Luigi Vanvitelli, and used during real work tasks execution.

The aim of this research is to propose an innovative method for a preventive ergonomic evaluation, creating a virtual workplace, using the Tecnomatix Process Simulate software by Siemens®, in which a mannequin simulates the whole task described by operation cards, assessing the EAWS index and validating the results in the physical world, using the proposed motion capture system.

According to this approach, it is possible to realize human-centered designed workplaces, allowing, on one hand, costs and time reduction, and, on the other hand, a workers' well-being improvement.

2 Virtual Ergonomics: Assessment Work Flow

Virtual ergonomics can be seen as the natural consequence of the technologies developed within Industry 4.0 and it represents for the companies a chance of safe workplaces designing, reducing drastically corrective interventions indicated by standard procedures.

The product development in a typical industrial environment, above all in automotive field, consists in four phases: style definition, design, engineering and production.

During both design and engineering phases, it is possible exploiting virtual reality technologies, applying Virtual Ergonomics techniques, which results in a preventive ergonomics approach, which allows to perform analysis and tests in a simulated environment, giving the possibility to anticipate problems solution, satisfying the international standards (Table 1).

Table 1. Technical standards and related ergonomic factor analyzed.

Technical standard	Ergonomic factor
EN 1005-4 ISO 11226	Postures
EN 1005-3 ISO 11228-2	Forces
EN 1005-2 ISO 11228-1/2	Manual handling of loads
EN 1005-5 ISO 11228-3	Upper limbs

In particular, as written above, during both designing and industrialization phases, EAWS is the ergonomic risk assessment method applied as screening tool of first level for the evaluation of biomechanical overload risks. The method is designed to evaluate all kind of risks described in Table 1, linking corrective and preventive ergonomics, pointing out the main problems and offering design solutions to overcome them.

The EAWS checklist is composed by four section, each of which evaluates:

- working postures and movements with low additional physical effort;
- action forces of the whole body or hand/finger system;
- manual material handling;
- repetitive loads of the upper limbs.

In order to fill-in the checklist, several physical parameters are necessary to be evaluated (joint angles, forces, pressures, reaction forces, accelerations, etc.) that would require the use of several tools (i.e. motion capture systems, dynamometers, electromyography) for a proper design of the workstation. This is particularly ambitious when the development of a new product needs a new design of assembly lines, because of the high number of workstations.

Thanks to virtual ergonomics it is possible to overcome these problems. Applying DM tools, it can be realized a virtual model of the plant that contains virtual models of the car components and all resources of the production plant (robots, tools, equipment, etc.). Inserting digital human models, able to simulate operating tasks of each workstation, a human-centered design is possible, based on the Ergo-UAS method.

2.1 Work Flow

In order to increase the reliability of a human-centered design of the workstations, based on Ergo-UAS system, by means of VR technologies, this paragraph will describe the work flow for the best implementation of the method proposed by this research.

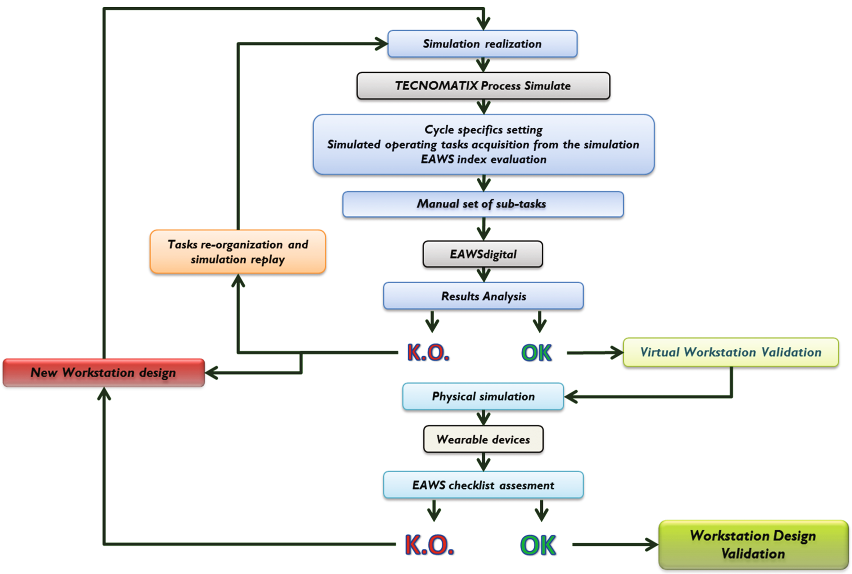

Fig. 1. Human-centered workstation design: work flow.

The work flow shown in Fig. 1, starting from a preliminary design of the workstation based on operation cards, is composed by two macro-steps:

– virtual analysis and validation;
– physical analysis and definitive validation.

2.2 Virtual Analysis

For the virtual simulation step, two softwares are used: TECNOMATIX PROCESS SIMULATE by Siemens® and EAWSdigital by MTM®.

Process Simulate is a PLM software that allows to create a virtual scenario in which one or more workstations, or the whole work line, can be created. In that scenario, the software module “Human” allows to create a digital cinematized mannequin, having realistic biomechanical properties, composed by 71 segments and 69 joints, whose ranges of motion are natural, on the base of results from several NASA studies [19].

The digital mannequin is able to carry out all tasks that characterize the workstation. He can pick and place objects, apply forces, push and pull carts, handle loads, simulate several operations (Fig. 2).

Process Simulate allows to realize both time-based and event-based simulations. The proposed method is based on the first one.

Once the simulation is completed, a tool integrated in the Process Simulate software, called EAWSdigital for Tecnomatix, is able to acquire the whole simulation, to divide it in a number of subtasks that depends on the set sampling time.

Once the simulation has been acquired, it is possible to evaluate the EAWS index by the EAWSdigital software by MTM®, that can be used standalone or integrated in Process Simulate software environment. EAWSdigital is able to fill-in all the EAWS sections, allowing the manual characterization of each acquired sub-task.

Once EAWS index is evaluated, it is possible to validate the virtual workstation in case of green value and re-organize the simulation, or design a new workstation, in case of red value.

2.3 Physical Analysis

Once the virtual workstation has been validated, physical tests are necessary in order to deliberate the workstation design definitively.

The main analysis concern postural aspects end efforts exerted by the workers. These parameters can be evaluated operating on the Body in White car or by means of immersive reality technologies (Fig. 2) applied to physical workstation as previously virtually designed. The use of wearable devices is necessary for a proper analysis.

Fig. 2. Example of 3D immersive reality.

Motion tracking devices represent an important research area for ergonomic issues. A research team from the department of Industrial and Information Engineering of the University of Campania Luigi Vanvitelli realized a motion tracking system, based on inertial sensors, able to accurately estimate the orientation of specific body segments.

The system, described in the next chapter and already presented at AHFE2016 [2], can be used to analyze the postural angles trend, to evaluate static (symmetric or asymmetric) postures and to validate the virtual workstation analysis, filling-in the EAWS checklist. Other devices can be used to estimate arms/fingers forces.

From EAWS index evaluated by physical analysis it is possible to validate the designed workstation. In case of red value a new design is necessary to iterate a new analysis cycle.

3 Body Motion Tracking

One of the first work in which inertial sensors were used to measure human movements for health purposes was in the 1950s [9]. However, until MEMS sensors were not commercially available, the development was impossible.

In the last decade, motion tracking systems have been strongly developed, for general purpose applications. Surely, from the point of view of sensors, the main reason is related to smartphone evolution. Activity tracking and human motion analysis are becoming a new market area for the so-called health applications [3–5].

As MEMS inertial sensors are compact and light, they have been a popular choice for applications such as motion tracking, human-computer interface, and animation. Some interesting uses is described, for example, in [10], where the study of the difference between static and dynamic activities using uniaxial accelerometers is reported. Similar methods have also been reported in [11–13, 15].

One of the most important problem that affects the application of inertial sensors in a poorly controlled environment is the drift.

As a possible solution, robotics or mechatronics (i.e. [16]) have been explored due to their stable and reliable performances. These robotic systems use potentiometers or gyroscopes to estimate limb rotation. Other sensors such as CCD cameras can be integrated within an inertial based system so as to mitigate drifts [17].

As in [6–8], in this paper multiple micro inertial measurement units (IMU) are involved to analyze human poses. A Kalman filter is used to compute the estimation of the attitude for each IMU, by combining a series of measurements affected by noise and other uncertainties.

Schematically speaking, the upper limb can be considered as composed by five segments/bones on which we will focus our attention: the trunk, two arms and two forearms. Hands will be neglected in this work, because in phase of development. Considering the legs in a steady state, bones' attitude estimation allows to compute the whole upper-body pose. Each segment can be equipped with a complete Inertial Measurement Unit, composed by a tri-axial accelerometer, a tri-axial gyroscope and a tri-axial magnetometer and used to estimate the orientation in a fixed frame.

The orientation of the fixed frame XEY_EZ_E is such that the Z axis is parallel to the gravity vector, the x axis points to the right of the body at the initial time and the y axis creates a left-handed reference system with the other two axes.

Each segment has a local frame in agreement with its orientation that is overlapped to the fixed frame at the initial time. The orientation of each segment can be determined using the Tait-Bryan angles that describe a rotation around the z axis (ψ yaw angle), a rotation around the y axis (θ pitch angle) and a rotation around the x axis (ϕ roll angle). This global orientation relates the flexion-extension angles of arms with the global roll angle $\phi \in [-\pi, \pi]$.

To avoid singularities, a quaternion based orientation for each segment is used. Quaternion $\boldsymbol{q} = [q_1, q_2, q_3, q_4]^T$ can be defined as follows:

$$\begin{cases} \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix} = \boldsymbol{r} \sin\frac{\phi}{2} \\ q_4 = \cos\frac{\phi}{2} \end{cases}$$

Where $\boldsymbol{r} \in \mathbb{R}^3$ is the unit vector and ϕ is the rotation of the reference system about $\boldsymbol{r}$. Note that the elements of the quaternion satisfy the condition:

$$q_1^2 + q_2^2 + q_3^2 + q_4^2 = 1$$

The transformation of an arbitrary vector $\underline{x}$ between the fixed frame ($\mathcal{E}$) and the local frame ($\mathcal{B}$) can be written as follows:

$$\underline{x}^b = \underline{\underline{C}}_{BE}(q(t))\underline{x}^E$$

Where $\underline{q} = [q_1, q_2, q_3, q_4]$ is the quaternion vector and $\underline{\underline{C}}_{BE}$ is the rotation matrix defined as follows:

$$\underline{\underline{C}}_{BE}\left(\underline{q}\right) = \begin{bmatrix} q_1^2 - q_2^2 - q_3^2 + q_0^2 & 2(q_1q_2 - q_3q_0) & 2(q_1q_3 + q_2q_0) \\ 2(q_1q_2 + q_3q_0) & -q_1^2 + q_2^2 - q_3^2 + q_0^2 & 2(q_2q_3 - q_1q_0) \\ 2(q_1q_3 - q_2q_0) & 2(q_2q_3 + q_1q_0) & -q_1^2 - q_2^2 + q_3^2 + q_0^2 \end{bmatrix}$$

The transformation between q and the Euler angles is:

$$\psi = \tan^{-1}\left(\frac{2(q_1q_2 - q_0q_3)}{1 - 2\left(q_2^2 + q_3^2\right)}\right)$$

$$\phi = \tan^{-1}\left(\frac{2(q_2q_3 - q_0q_1)}{1 - 2\left(q_1^2 + q_2^2\right)}\right)$$

$$\theta = \sin^{-1}(-2(q_1q_3 + q_0q_2))$$

The upper limb pose is composed of an absolute orientation of the trunk, plus the relative orientation of arms about shoulder and the relative orientation of forearm about elbow.

Given the symmetry of the arm problem, generally speaking, let's call $\boldsymbol{q}_0$ the orientation of trunk, $\boldsymbol{q}_1$ the orientation of arm and $\boldsymbol{q}_2$ the orientation of forearm, the relative transformation matrices can be written as follows:

$$\underline{\underline{C}}_{01} = \underline{\underline{C}}_{BE}(\mathrm{q}_1)\left(\underline{\underline{C}}_{BE}(q_0)\right)^T$$
$$\underline{\underline{C}}_{02} = \underline{\underline{C}}_{BE}(q_2)\left(\underline{\underline{C}}_{BE}(q_0)\right)^T$$
$$\underline{\underline{C}}_{12} = \underline{\underline{C}}_{BE}(q_2)\left(\underline{\underline{C}}_{BE}(q_1)\right)^T$$

Where $\boldsymbol{C}_{01}$ is the transformation matrix between trunk and arm, C_{02} is the transformation matrix between trunk and forearm and C_{12} is the transformation matrix between arm and forearm.

4 Test Case: Results

In order to validate the innovative procedure for ergonomic index evaluation, proposed by this research, a test case has been implemented.

The test consists in carrying out a simple activity in which the worker takes two parts, one with left hand and the other with the right one, from a 1.7 m high shelf, overlapped them and keeps on with a tightening on a 1 m high worktable, by means of an eclectic screwdriver. At the end, the worker picks the assembly and places it in a cart, positioned on her right.

A female 5th percentile has been used as test worker.

The first step, as indicated by the workflow in Fig. 1, is the realization of the virtual simulation. In Tecnomatix Process Simulate® virtual environment, the workplace has been reproduced, respecting the dimension of the real one, represented by mechanics laboratory in which our research team works (Fig. 3).

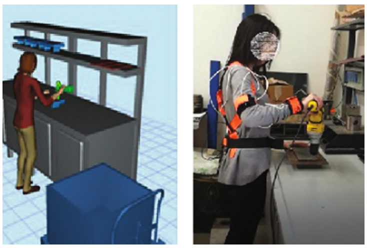

Fig. 3. Operating tasks in virtual and real environment.

Once carried out the simulation, the next step is characterized by experimental tests, in which the worker wears the motion capture system described above. The test has been repeated two times, at the end of which posture angles of trunk and upper limbs, derived from numerical and experimental tests, have been analyzed and compared. The Euler angles data, provided by the motion capture system, have been opportunely manipulated in order to plot posture angles required for ergonomic analysis.

About the angle trends analyzed afterward, that one from numerical data is plotted in red, while the others, from experimental data, are plotted in blue, for the first test, and in green for the second one.

First of all, trunk angles of flexion and lateral flexion have been analyzed.

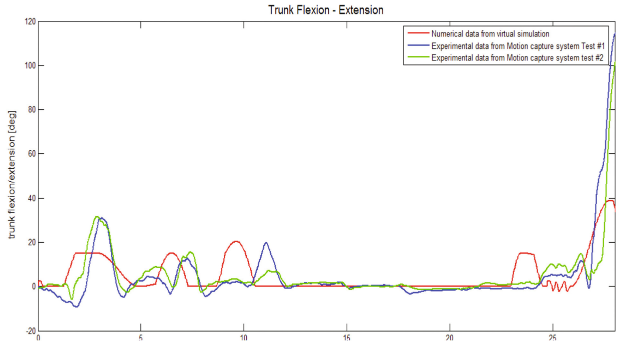

Fig. 4. Trunk flexion/extension angles.

Regarding trunk flexion-extension angle (Fig. 4), the experimental data substantiate the numerical one. Most of the task is carried out in standing posture, except in the final part, from the second 26 onwards, during which the worker flexes trunk to place the assembly in the cart.

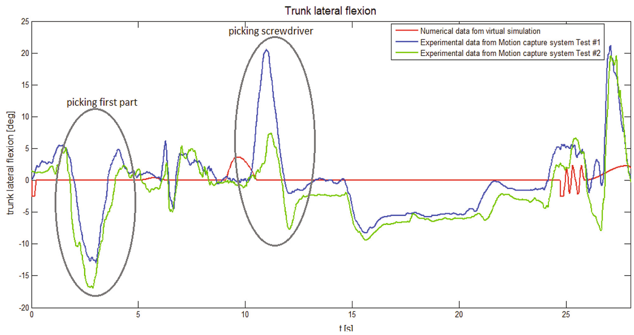

Fig. 5. Trunk lateral flexion angles.

The angle trends about trunk lateral flexion (Fig. 5) present some difference between numerical an experimental data, due to a more realistic way to carry out the task by the real worker respect to the virtual mannequin, where the first one flexes laterally her own trunk in picking the first part and the screwdriver (circled in grey).

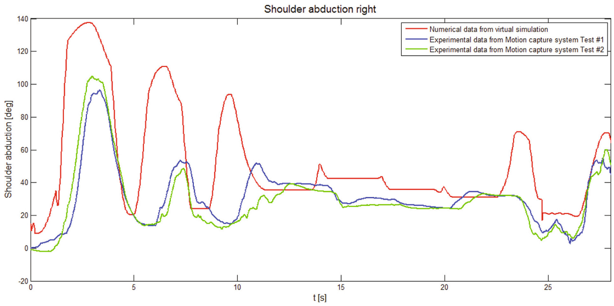

Fig. 6. Right shoulder abduction angles.

About shoulder abduction angles, for right (Fig. 6) and left (Fig. 7) limbs, the trends are qualitatively consistent, less than some pick values in picking tasks, because the worker flexes her own trunk in reaching the gripping zones.

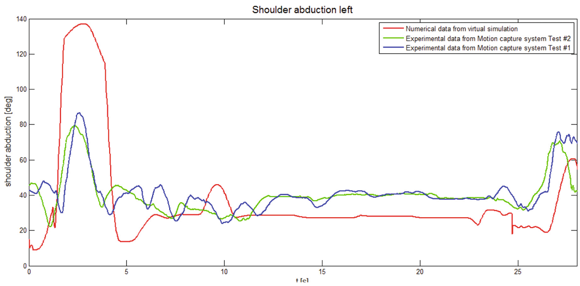

Fig. 7. Left shoulder abduction angles.

In the same way, also about shoulder flexion/extension angles, not shown in this paper, the trends are similar to abduction ones and qualitatively coherent.

The last angle trends analyzed (Figs. 8 and 9) regard the elbow flexion/extension, evaluated as the angle between arm and forearm.

About this angle, the experimental data trends are qualitatively coherent with the numerical one, except for right limb in test #2, in which the worker uses her forearm in a different way w.r.t. the test #1.

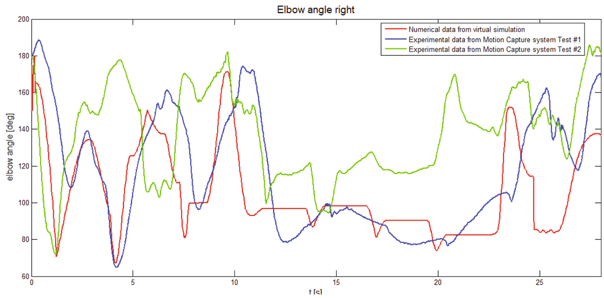

Fig. 8. Right elbow flexion/extension angles.

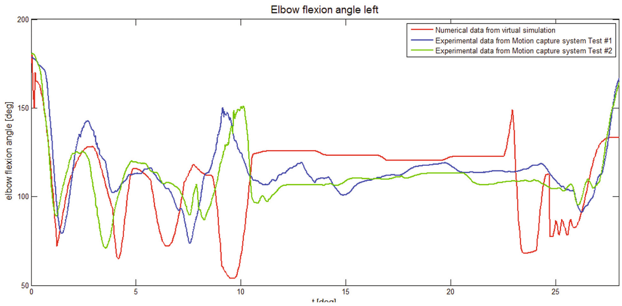

Fig. 9. Left elbow flexion/extension angles.

5 Conclusions

A preventive approach in workplaces design, based on ergonomic index evaluation in a virtual environment, is a fundamental activity to improve work organization and safety on the one hand and, on the other hand, to reduce time and costs, especially in the start phase of production.

Virtual simulations of operating tasks provide a high number of data, useful for preventive evaluations of ergonomic indexes, according to which workplaces can be efficiently designed.

This research proposes an innovative method of workplaces design that, starting from a preliminary design, validates its goodness, carrying out the operating tasks, on the base of operation cards and evaluating EAWS index in a virtual environment, thanks to specific software, as Tecnomatix Process Simulate® EAWSdigital®.

Once the virtual workplace is validated, to strengthen the design method, physical tests can be carried, using wearable devices and replicate in laboratory, or in a virtual immersive environment, in order to acquire data helpful to fill-in the EAWS checklist. For this research, a motion capture system realized by a research team of Dept. of Industrial and Information Engineering from University of Campania has been used.

Comparing posture angles trends, the results prove that the method proposed is ready to be applied and to give support to ergonomist and designer for a human-centered factory design.

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