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Workplace design ergonomic validation based on multiple human factors assessment methods and simulation

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ABSTRACT

According to the international literature postures, exerted forces, manual handling and repetitive actions with upper limbs must be considered in order to estimate the workers' exposure to biomechanical overload risk, but also a preventive ergonomic approach in the design phase is possible. Within the Industry 4.0, the digitalisation of manufacturing processes generate benefits in terms of production costs and time. Regarding the ergonomics, it is possible to set up a predictive model for the evaluation of biomechanical overload risk. This paper proposes an appraisal of a workplace design and ergonomics validation procedure based on simulation: data from assembly tasks simulation of Digital Human Models (DHM) can be used to assess the ergonomic indexes (OWAS, NIOSH, OCRA, EAWS, etc.). So, it is possible to preventively solve ergonomic risks during the design phase. A test case, regarding a real workplace of an assembly line of an important automotive Company, is also presented.

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KEYWORDS
Workplace design; human-centred design; industrial ergonomics; simulation

1. Introduction

Assembly lines of manufacturing industries are very complex to design. In particular, those ones related to automotive industries are dedicated to produce a large volume, up to 800 cars per day, of multiple product models. Hence, the production processes are affected by several variables, such as technological, environmental, logistics and ergonomics. Taking all these variables into account should lead to an optimal design of the lines and, in particular, of the workplaces.

Assembly line design methods do not consider properly these variables during the several phases of the product and the production design as demonstrated by (Abdullah, Popplewell, & Page, 2003). In particular, ergonomics aspects are often coarsely considered during the design phase. This means applying only corrective ergonomic measures during the production phase, when the costs to solve problems are high and the production risks a stop for allowing possible interventions on the line (Dul & Neumann, 2009). This feeling has been recently confirmed by (Falk & Rosenquist, 2014) so that some authors tried to integrate the ergonomics during the design of workplaces (Caputo, Greco, Fera, & Macchiaroli, 2019; Sun et al., 2018).

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During the last years, the new information and communication technologies are leading the world of manufacturing industry to a period of changes, a new industrial revolution named Industry 4.0. This new paradigm can be seen as the follow-up of the ideas developed in the past by CIM – Computer Integrated Manufacturing that proposed to control the whole production process by using computers. Industry 4.0 focuses on the use of digital technologies that allow higher interconnections between the resources, humans and systems, of the company. One of the purposes of Industry 4.0 is to facilitate the realisation of the digital factory, in which, simulating the real world, it is possible detecting problems preventively and making decision based on complex numerical analyses.

One of the main pillar of Industry 4.0 paradigm is represented by Virtual Reality (VR), in particular by its industrial declination, named Digital Manufacturing – DM, that integrates a wide set of technologies to support the production, from the design to the product realisation, monitoring and optimising the production processes (Chryssolouris, 2008; Kuehn, 2006).

The use of aided design software reduces product and production processes design times, responding more rapidly to current market demand. DM mostly reduces costs by identifying any production critical situation before its real industrial implementation; moreover, it allows eliminating some phases of traditional productive process as physical prototypes realisation and testing, with a relevant reduction of production starting times.

Digital systems allow setting the best plant layout, optimising the use of automated machine, implementing robot kinematic and human ergonomic tests and studying human-machine interactions.

From an ergonomics point of view, DM gives the opportunity to reproduce workplaces in a virtual scenario, where it is possible to simulate manual assembly tasks and to evaluate ergonomic workplaces performances.

The numerical assessment of ergonomic risk indexes allows identifying critical issues since preliminary design phases of the products and of the associated production processes, allowing virtual design changes before accessing to the physical production line. This preventive approach, known as virtual ergonomics, can be seen as the natural consequence of the use of technologies involved in the Industry 4.0 panorama, and it represents a chance for the companies to design safe workplaces, drastically reducing corrective interventions indicated by standard procedures.

During both designing and industrialisation phases, it is possible to apply any ergonomics assessment method for the evaluation of biomechanical overload risk, based on the evaluation of the main source factors (awkward postures, exerted forces, manual material handling (MMH) and repetitive actions), pointing out the main problems and offering design solution to overcome them.

Evaluating ergonomic indexes means evaluating several physical parameters (joint angles, force, pressures, etc.), that require the use of many tools (i.e. motion capture systems, dynamometers, electromyography, cyber-gloves) for a proper design of the workplace. This can result complex when the development of a new product needs a new design of the assembly lines, in which the number of workplaces is very high.

Virtual ergonomics approach allows overcoming these troubles creating a virtual model of the plant that contains virtual models of products and related components, as shown in the following sections. In this virtual scenario, a Digital Human Model (DHM) is able to reproduce operating tasks of each workstation dynamically and a computational evaluation of indexes is carried out, making possible a human-centred design of the workplace. In recent years, several commercial software have been developed and, in some researches, classifications of these tools have been proposed in relation to different criteria for their use in the design phase (Poirson & Delangle, 2013).

During the last years, several researches have been led in order to investigate the possibility to introduce numerical model for industrial ergonomics applications: Alkan, Vera, Ahmad, Ahmad, and Harrison (2016) propose a postural risk evaluation method at early design stage; Glaeser, Fritzsche, Bauer, and Sylaja (2016) investigate on the latest development about the implementation of automatic ergonomic assessment; Lawson, Salanistri, and Waterfield (2016) investigate the academic literature in order to give the basis for future developments of VR technology application for automotive industries.

As it is possible to find in Vitiello, Galante, Capoccia, and Caragnano (2012) and in Caragnano and Lavatelli (2012) in Fiat Chrysler Automobiles (FCA) preventive ergonomic approaches in designing new workplaces have been adopted during the last years, applying the Ergonomic Assessment Work-Sheet (EAWS) as second level ergonomics screenings during both Process/Product Design and Process Industrialisation phases.

In order to achieve these results, a lot of information, principally related to human factors, are necessary to satisfy mandatory ergonomic standards in terms of safety. In fact, at Mirafiori Plant, researchers from FCA created an 'ergonomics laboratory', called *ErgoLab*, where many physical parameters are assessed, reproducing a real workplace, with a real Body in White car, in which different manual tasks are carried out by a worker. The main analysis concerns postural aspect and effort exerted by the workers by means of innovative tools (Spada, Germanà, Sessa, & Ghibaudo, 2015).

As reported in Hovanec, Korba, and Solc (2015) and Makarova, Khabibullin, Belyaev, Mavrin, and Verkin (2015), exploiting the advantages of digital manufacturing, processes' parameters and ergonomic indexes can be investigated in a virtual environment, where manual tasks are simulated. In this context, the use of validated human models becomes crucial. Recent researches, as (Caputo, Greco, D'Amato, Notaro, & Spada, 2018; Caputo et al., 2019) validated the numerical models based on the use of DHM implemented in Tecnomatix Process Simulate software environment by Siemens®. The numerical model has been validated by comparing both the biomechanical behaviours of the DHM with those of a real human counterpart and the numerical results with the experimental ones in assessing EAWS index. This allowed to make the numerical simulations reliable for a preliminary assessment of the workplaces' ergonomic performances already at the design phase.

The aim of this research, showing a real case study, is to propose an appraisal for the workplace design and a validation procedure based on preventive ergonomics evaluation by reproducing a virtual workplace, within Tecnomatix Process Simulate by Siemens® software environment, in which a DHM simulates the whole task described by Standard Operation Procedure (SOP). The numerical data have been used to assess the ergonomic indexes (the compulsory ones for the Italian safety norm, i.e. not EAWS for example) whose values preliminarily validate, or not, the workplace design. Applying this procedure leads to realise human-centred designed workplaces, allowing both costs and time reduction and the well-being improvement for workers.

2. Materials and methods

2.1. Regulations

In Europe, the protection system of health and safety of workers in a workplace is set-up by EU-Machinery Directive (DIR06, 2006) and EU-Framework Directive (COU89, 1989), which demand ergonomic risk analysis to be carried out in various phases of the product lifecycle. The main standards for ergonomics are listed in Table 1.

In Italy, the application of these standards is mandatory during the production phase, using the standard methods according to current national laws, according to the Legislative Decree 81/2008 about the safety at work.

According to Figure 1, which shows the product and production process development timeline, during the production phase it is only possible a corrective ergonomic approach whilst any ergonomic standard is not mandatory during design and industrialisation phase, where it is possible to apply first level ergonomic screenings based on ISO 11228-1, -2, -3 (ISO, 2003, 2006, 2007) for manual handling and on ISO 11226 (ISO, 2000) for static working postures in order to assess the ergonomic performances of the workplace, as described in ISO TR 12295 (ISO, 2014).

2.2. Ergonomic risk indexes evaluation methods

Literature investigation about workload assessment methods and procedures have been conducted to be able to evaluate the ergonomic factors of Table 1 in a real scenario. In particular, Takala et al. (2010) analysed scientific databases for biomechanical workload

Table 1. Techinical standards and related ergonomic factor analysed.

	European Union Directives	
Ergonomic factors	Machinery Directive	Framework Directive
Postures	EN 1005-4	ISO 11226
Forces	EN 1005-3	ISO 11226-2
Lifting (and carrying)	EN 1005-2	ISO 11228-1
Push and Pull		ISO 11228-2
Upper limbs	EN 1005-5	ISO 11228-3

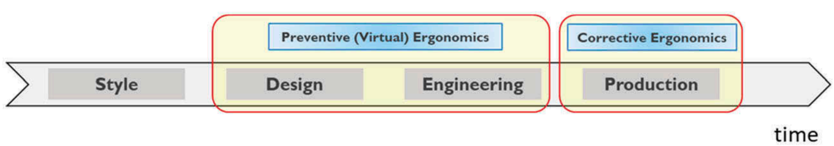


Figure 1. Product development phases in automotive industry.

assessment methods from 1965 to 2008, by cataloguing them and by investigating about their applicability, their parameters of interest and their advantages and disadvantages.

In this paper, the assessment methods described in Table 2 (OWAS, Force Solver according to Snook and Ciriello tables, NIOSH equation and OCRA) have been selected due to their wide use by the main multinational manufacturing companies. Most of them can be evaluated by means of specific tools in the Tecnomatix Process Simulate by Siemens® software. Although the use of Snook and Ciriello tables, NIOSH equation and OCRA checklist is widespread in manufacturing companies for the assessment of risk due to force exertion, material handling and repetitive actions, it is worth to note that in this paper to assess the risk due to working postures, the OWAS method has been selected for several reasons. First of all, it is easily implementable in the simulation software used (i.e. Tecnomatix Process Simulate®). Moreover, while for the other ergonomics risk sources the methods used are very consolidated in their practical use (e.g. NIOSH, OCRA, etc.) for the postural risk assessment it is not possible to identify a unique way to measure its risk impact, so several methods can be applied. The OWAS was selected, even if aged, for the reason that it can be easily applied to working tasks typical of the manufacturing systems that are commonly associated with dynamic behaviours of the humans, while other methods, as REBA (Hignett & McAtamney, 2000), are more focused on static or near-static behaviours of the humans.

There are several companies, such as FCA, that apply EAWS for assessing the biomechanical overload risk from a holistic perspective during the design phase of the workplaces and for validating the design itself from an ergonomic point of view, even if the use of first level screening is not mentioned in the Italian Legislative Decree 81/2008 about the safety at work. On the other hand, many other companies, especially Small and Medium Enterprises (SMEs) ones, do not have expertise about the use of complex assessment methods, such as EAWS, and the use of the numerical procedure presented in the following sections, based on the application of the most common assessment methods during the design phase, can equally ensure the realisation of safe workplaces.

2.3. Workflow

The workflow, described in this section, is purposed to support the application of a workplace (WP) design validation procedure.

Considering the ergonomic evaluation methods of Table 2, the procedure is based on the analysis of the four factors sources of biomechanical overload (working posture, forces, manual material handling (MMH) and repetitive actions with upper limbs), according to their risk indexes.

Figure 2 shows the iterative procedure that lead to validate the WP design, basing the decision on the ergonomic evaluations.

The aim of the workflow is to support assembly line designers that, thanks to continuous information exchanges with the ergonomists, can design the workplaces taking into account also the ergonomic variables, reducing the ergonomic risks of occupational injuries. Moreover, exploiting the advantages of the numerical simulation as supporting tool, the analysis can be carried out in a virtual environment, according

Table 2. Workplace ergonomics assessment methods.

Factor	Method	Short description	Risk index areas
Postures and Low Exerted Forces	OWAS (Kharu, Kansi, & Kuorinka, 1977)	OWAS method evaluates the load handles (three categories) and the assumed postures of back (four postures), arms (three postures) and lower extremities (seven postures), resulting in 252 possible combinations, classified in four action categories indicating needs for ergonomic changes. The risk index is detailly defined in section 3.1.1.	OWAS Risk Index 100: No risk 100÷200: Low Risk 200÷300: Medium Risk 400: High Risk
Forces	Force Solver (Siemens PLM Software Inc., 2017)	Force solver is an algorithm, integrated in Tecnomatix Software by Siemens, that numerically analyses the maximum force that a human model can exert in a particular posture and along a specified direction. It is based on the University of Michigan strength models of maximum voluntary exertions (MVEs) and on the Psychophysical Tables of Snook and Ciriello.	-
Manual Material Handling	NIOSH lifting equation (Waters, Putz-Anderson, Garg, & Fine, 1993)	The method assesses the risk of low back disorders in job activities with repeated lifting. The lifting index is the ratio of the actual weight handled to the recommended weight limit, which is evaluated by considering the distances of the handled object, the body posture, the frequency and duration of the task and the type of grip on the handled object. For a precise reference to the math form of this equations please refer to the literature.	NIOSH Lift Index ≤0.85: Low Risk 0.86÷0.99: Medium Risk >1: High Risk
	Snook & Ciriello procedure (pushing/pulling actions) (Snook & Ciriello, 1991)	The procedure is based on the so-called "Psychophysical Tables", which provide important information on the capabilities and safe limit loads of manual load handling operations. These tables describe the recommended limit values for Pushing/Pulling actions, showing the maximum initial (IF) and the maximum sustained (SF) forces recommended for the healthy adult working population as a function of: sex, displacement distance, frequency of actions and height of hands from the ground.	S&C Risk Index ≤0.85: Low Risk 0.86÷0.99: Medium Risk >1: High Risk
Repetitive actions with upper limbs	OCRA checklist (Colombini, Occhipinti, & Alvarez-Casado, 2013)	The high precision OCRA checklist is used for the calculation of a synthetic index of exposure to repetitive movements of the upper limbs. The method also considers and assesses four main collective risk factors based on their respective duration: ● Lack of proper recovery periods; ● Repetitiveness (frequency or actions); ● Force values; ● Awkward postures and movements. The synthetic index of exposure derives from the ratio between the daily number of actions actually performed with the upper limbs in repetitive tasks and the corresponding number of recommended actions.	OCRA checklist Risk Index ≤5: No Risk (Excellent) 5.1÷7.5: No Risk 7.6÷11: Very Low Risk 11.1÷14: Low Risk 14.1÷22.5: Medium Risk

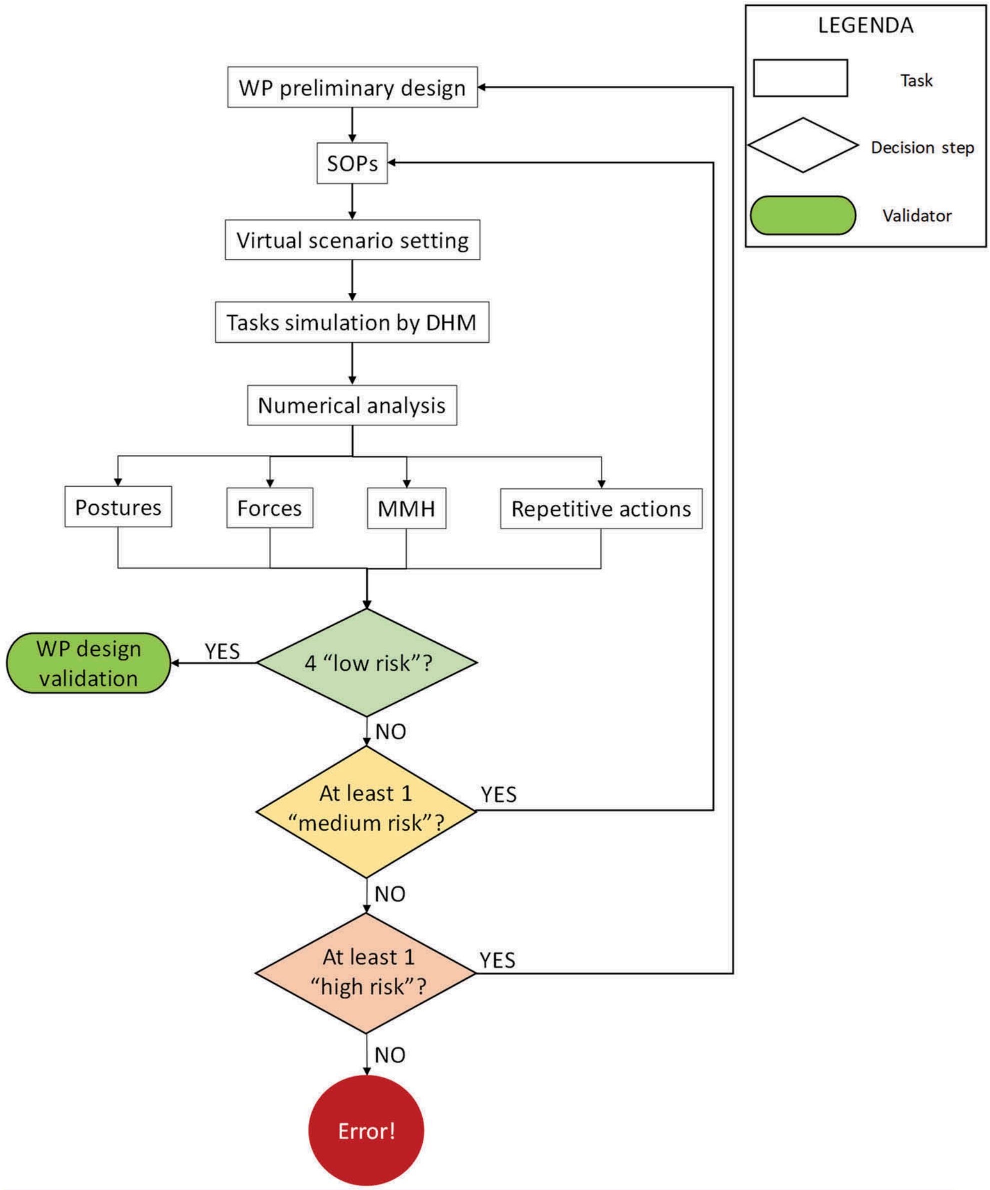


Figure 2. Virtual human-centred workstation design validation: workflow.

to DM approach, making possible any design change with a minimum cost expense, related only to the time taken by the designers for the changes.

The iterative procedure starts from a **preliminary design** of the workplace that strictly depends on the assembly line layout definition and on the production needs. Often, this step is also based on the past experience about the production systems for previous produced products, especially for the big OEM (Original Equipment Manufacturer).

The second step is characterised by SOPs (Standard Operating Procedures) definition and a first times estimation: SOPs represent a set of step-by-step instruction, depending on the component to be assembled and on the know-how of the engineers, for assisting the workers in carrying out the working activity properly. Once the SOPs are defined, the working time can be estimated according to the MTM (Method Time Measurements). It is worth to note that this is a first attempt to define SOPs, that will be optimised if the workplace does not meet the ergonomics requirements.

At this point, it is possible to set the virtual scenario by using a Virtual Reality simulation software that allows simulating the production processes, as shown in Figure 3. For completing this step, it is necessary to have the CAD files of the products and the resources, the SOPs and a database of Digital Human Models.

Once the WP is set, it is possible to use the DHM, customised according to the desired anthropometric measures, to simulate the operating tasks. There are several DHMs available, some of which can be easily downloaded from the network. The most complex DHMs are cinematised with realistic biomechanical properties, composed by a high number of segments connected by joints made up of all d.o.f. (degrees of freedom) corresponding to the real human articulations. Their anthropometry can be customised according to the characteristics of the workers' population. A DHM is able

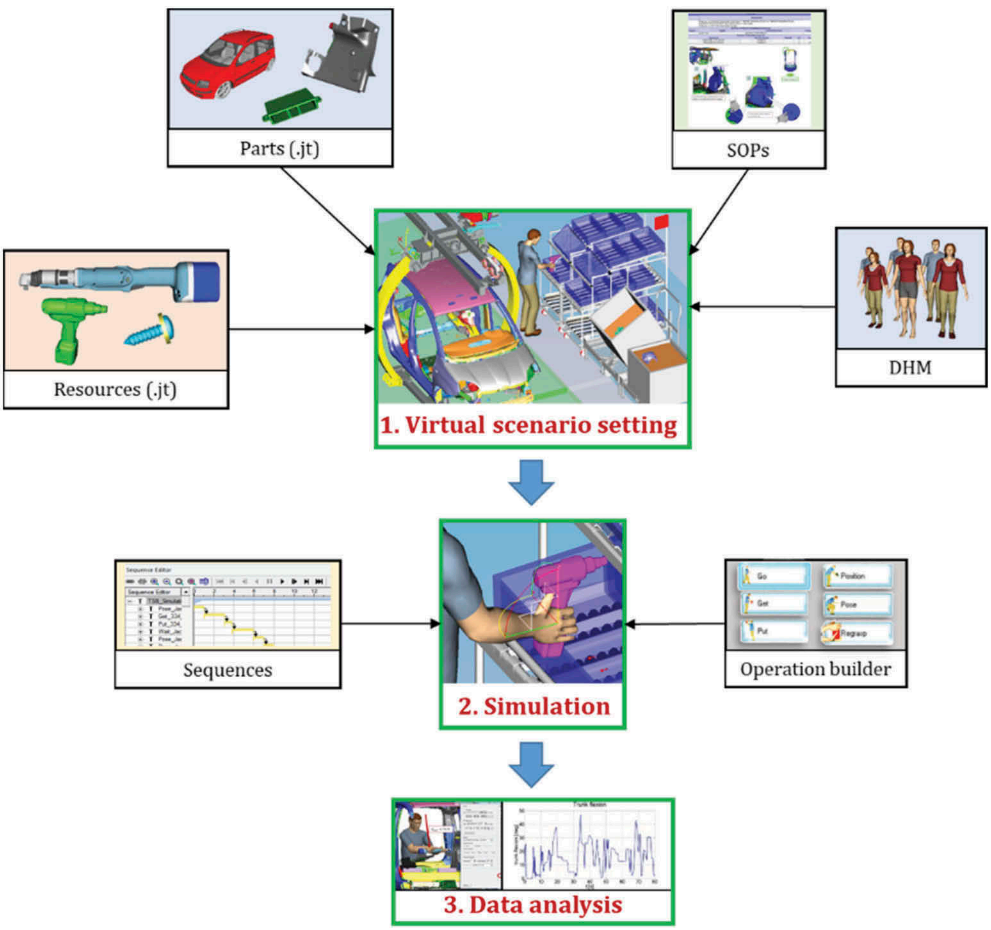


Figure 3. Time-based simulation workflow.

to simulate all the physical and part of the physiological behaviour in the working tasks that characterise the workstation. He can pick and place objects, apply forces, push and pull carts, handle loads, simulate several operations. Due to the extreme complexity, it is not yet possible to simulate the cognitive aspects.

The next step, namely the simulation, can be realised both time-based and event-based. For a preliminary ergonomic risk evaluation, a time-based simulation is enough. Once the line layout is defined, an event-based simulation allows simulating the whole production process, with multiple product models, and other ergonomic screenings, such as human fatigue, can be performed also recognising the real feasibility of the SOP previously designed.

Once the simulation is completed, numerical data can be extracted for the ergonomic evaluation. In a manufacturing industry, such as the automotive ones, the so-called second level screenings described in Table 2, needs to be evaluated. The numerical evaluation can be carried out by using specific tools already implemented in the software or by using self-made codes.

The decision-making process, i.e. the low part of the workflow in Figure 3, determining the exit condition from the iteration, is based on the four evaluated risk indexes, as follows:

- all the four risk indexes are in the 'Low-Risk Area': the design can be validated, and the iterative process is completed;
- At least one of the four risk indexes is in the 'Medium Risk Area': it is necessary to re-define the SOPs by re-ordering operations in such a way as to reduce the risk index or increasing recovery times per cycle;
- At least one of the four risk indexes is in 'High-Risk Area': it is necessary to modify or provide a new WP design, based on the ergonomic feedback done by the previous iteration.
- If none of the above conditions are verified, there is an error in the procedure that needs to be restarted.

Alternatively, in this step, according to ISO TR 12295 (ISO, 2014), it is possible to apply also first-level screenings for a quick ergonomic assessment.

2.4. Test case and simulation

In order to explore the possibility and the reliability of ergonomic indexes computation based on simulations, a workplace of 'Fiat Panda' assembly line from Fiat Chrysler Automobiles (FCA) *Gianbattista Vico Plant* in Pomigliano d'Arco (Naples) has been considered as test case. The workstation had been designed by FCA engineers respecting ergonomic requirements as suggested by Machinery Directive and ISO TR 12295, evaluating static working postures, exerted forces, material manual handling and repetitive loads on upper limbs.

The Virtual Reality Software used to carry-out the test case is Tecnomatix Process Simulate by Siemens®.

Process Simulate is a PLM software that allows to create a virtual scenario in which one or more workstations can be set. In that scenario the module 'Human' allows to create a DHM, named Jack, composed by 71 segments and 69 joints whose range of motion are ‘natural’, based on various studies by researchers from the United States (US) National Aeronautics and Space Administration (NASA, 1987) and widely used for numerous researcher such as (Demirel & Duffy, 2007; Stephens & Godin, 2006).

The DHM used for this test case is a 50th percentile (P50) of ANSUR database (Gordon et al., 2014). This anthropometric database represents one of the most comprehensive collection of body-size in the world and it is related to the US Army population. The database is already implemented for the Jack anthropometric customisation. It is worth to note that other anthropometric databases can be implemented for customising the DHMs. During the design, it is necessary to consider that the workplace must accommodate the 90% of the workers’ population and usually the 5th female (P5) and the 95th male (P95) percentiles are used for evaluating the ergonomic indexes. In this case study, a P50 has been chosen for just demonstrating the applicability of the proposed procedure.

The task carried-out in this workstation is characterised by three main activities: bar code reading on the front zone of the car, rear window ground and audio unit connection and rear sound adsorbing panel assembly on the rear zone of the car.

Figure 4 shows the scenario in which the car is positioned on a skillet. There is a container for the sound absorbing panels on the right side of the workplace, and there is a dolly cart, moved by the workers, that contains other components and equipment.

The distances between the equipment are described in Figure 5.

According to the SOP, provided by FCA, the activities can be schematically described as shown in Table 3. The working time of each sub-task is compliant with MTM (Method Time Measurements) and its evolutions, the most known and applied methods for predicting working time in a typical batch production system. By dividing the task in micro movements (reach, grasp, position, release, move and so on), it allows determining times without using the chronometer (Maynard, Stegemerten, & Schwab, 1948). The MTM process language is widely employed for the management of the production, for modelling human movements and for the design of productive and healthy workplaces (Baraldi &

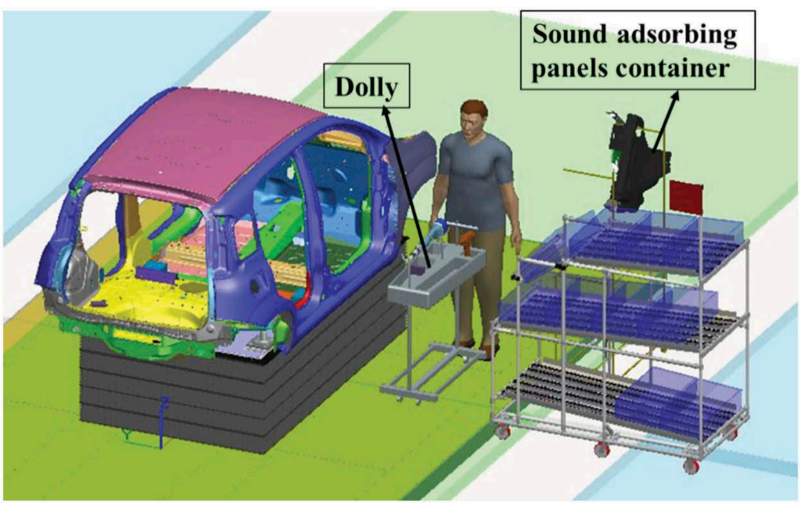


Figure 4. Virtual scenario.

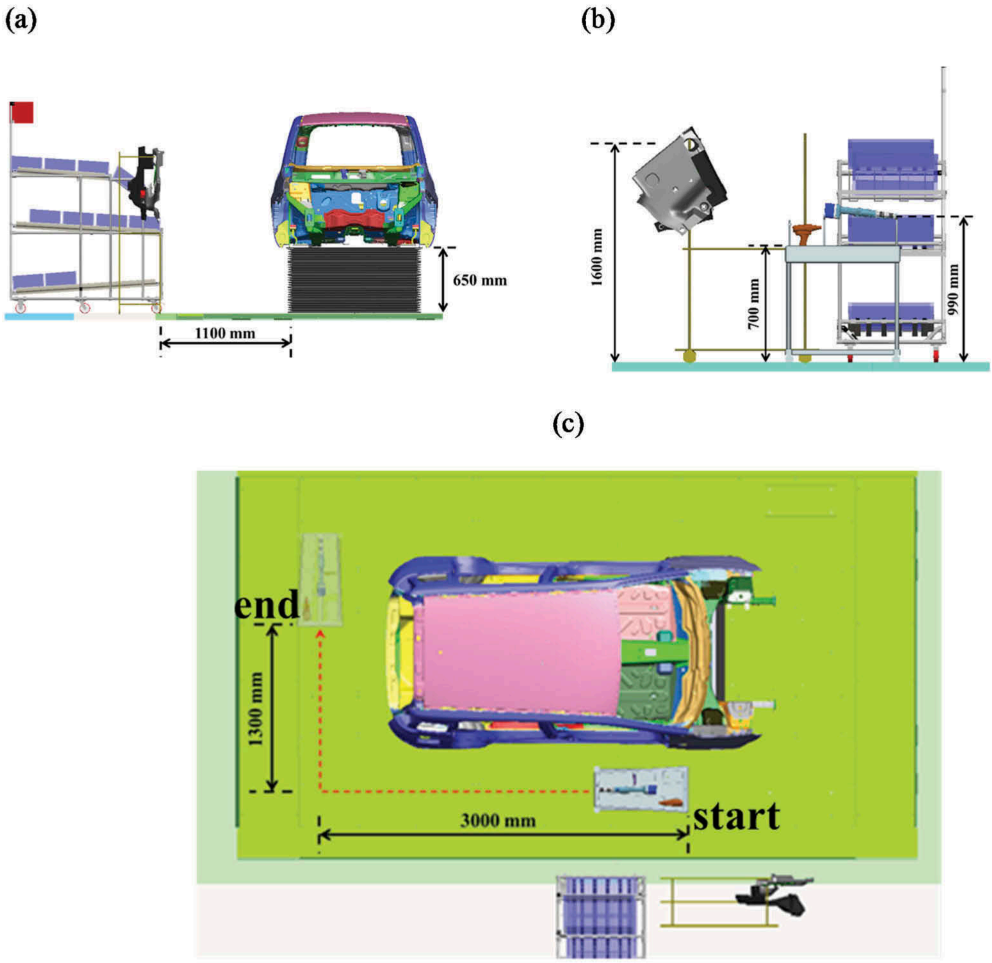


Figure 5. Distances between equipments.

Kaminski, 2011; Das, Shikdar, & Winters, 2007; Freivalds & Niebel, 2014; Goover, 2014). In addition to the operations order, the SOP describes also the equipment selected to be used by the workers, so no selection by the authors was made about the SOP specifications and equipment to use.

Table 4 describes the main properties of the parts to be assembled and the equipment used by the worker. These properties have been provided by the Company. In detail, according to the tasks numbering of Table 3, about the equipment the resource screwdriver #1 is used for carrying out the tasks 1,2, 3, 7 and 8 while the resource screwdriver #2 is used for carrying out the tasks 12, 13, 14, 15 and 16.

The screwdrivers, the audio unit, the connector and the screws are contained in a dolly cart (see Figure 4) that can be moved within the workplace area. The sound absorbing panels are hanged on a container and, after the picking, they are carried by the workers with the right hand.

The following Table 5 shows the simulation frames corresponding to the sub-tasks described in Table 3.

Table 3. Test case 1: schematic description of the activity.

Rear window ground and audio unit connection, rear sound adsorbing panels assembly		
Cycle time		80 s
Gender		Male P50
Main tasks		**Sub-tasks**
Bar code reading and dolly carrying	1	Pick bar code reader from the dolly
	2	On the front of the car, position reader and read bar code
	3	Place bar code reader on the dolly
	4	Pick rear sound adsorbing panels
	5	Carry the dolly to the back of the car
	6	Place panels on the car floor
Rear window ground and audio unit connection	7	Pick screwdriver#1 and connect rear window ground
	8	Place screwdriver#1 on the dolly
	9	Pick manual screwdriver, audio unit and screws
	10	Place audio unit on the car floor
	11	Insert screws using manual screwdriver
	12	Pick screwdriver#2 from the dolly
	13	Position screw on the tip of the screwdriver#2
	14	Place audio unit and perform two screwings
	15	Connect connector to audio unit
Panels assembly	16	Place screwdriver#2 on the dolly
	17	Pick and place right audio adsorbing panel
	18	Pick and place left audio adsorbing panel
	19	End of the task

3. Numerical results analysis and discussion

In this paragraph, the numerical evaluation of the ergonomic indexes described above are shown. In particular, the risk indexes of Figure 2 are evaluated according to ergonomic methods described in Table 2.

3.1. Working postures

3.1.1. OWAS

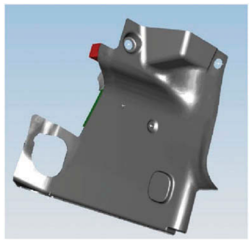
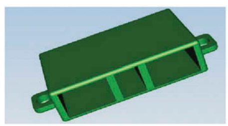
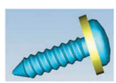
From the simulation, it can be extracted a high amount of data which allow to perform a detailed analysis of working postures. The most important data are those ones regarding posture angles, for which it is possible to plot the trends over the time for each one of the 71 segments of the virtual mannequin.

Figures 6, 7 and 8 show the main posture angles trends of upper body: trunk flection (Figure 6(a)), trunk lateral flection (Figure 6(b)), trunk torsion (Figure 6(c)), right arm elevation (Figure 7(a)), right elbow flection (Figure 7(b)), left arm elevation (Figure 8(a)) and left elbow flection (Figure 8(b)).

From the posture angles trends, the values and the durations they reach, it is possible to note that the assumed postures do not seem significantly onerous for the biomechanical overload due to working postures since, according to the Standard ISO 11226, there are not static awkward working postures (a posture is static if hold for at least four consecutive seconds) of trunk and upper limbs.

For this research, the OWAS procedure has been applied for studying the working postures. Even if OWAS (Kharu et al., 1977) is dated and not properly suitable for assessing static working postures, according to the Standard ISO 11226, it allows to identify, within a production cycle, the operations and/or phases potentially dangerous for the musculoskeletal system, quantifying the level of risk. The method analyses

Table 4. Parts and equipments properties.

Part/Resource	Figure	Mass	Other properties
Screwdriver #1 (including bar code reader)		2 kg	Right-handed tightening torque 3 N·m
Screwdriver #2		2 kg	Right-handed tightening torque 3 N·m
Sound adsorbing panel		0.5 kg	-
Audio unit		0.2 kg	-
Connector		0.1 kg	-
Screws		0.02 kg	Number 2

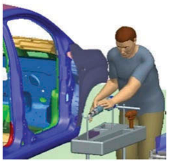
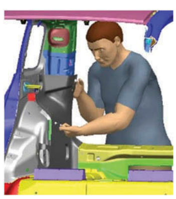
a worker's posture based on the position of the back, upper and lower limbs and the amount of lifted load. Each of these four is associated with an integer number, which identifies a given configuration (Figure 9).

The OWAS evaluation tool from Tecnomatix Process Simulate software enables to analyse operations according to predefined joint values. Running the simulation, it is easy to evaluate the different postures according to the OWAS method (Figure 10).

After the identification of the OWAS code, a multiple table is used to determine the risk class of musculoskeletal disorders.

The evaluation with the OWAS method must be carried out at fixed and predefined time intervals, the duration of which may vary according to the objectives set.

Table 5. Simulation frames corresponding to sub-tasks of Table 4.

Rear window ground and audio unit connection, rear sound adsorbing panels assembly: simulation frames			
			
1	2	3	4
			
5	6	7	8
			
9	10	11	12
			
13	14	15	16
			
17	18	19	

A lower interval corresponds to a greater accuracy of the survey (Brandl, Mertens, & Schlicl, 2017).

The OWAS calculation tool analysed 58 working postures during the working cycle (80 s) characterised as resumed in Table 6:

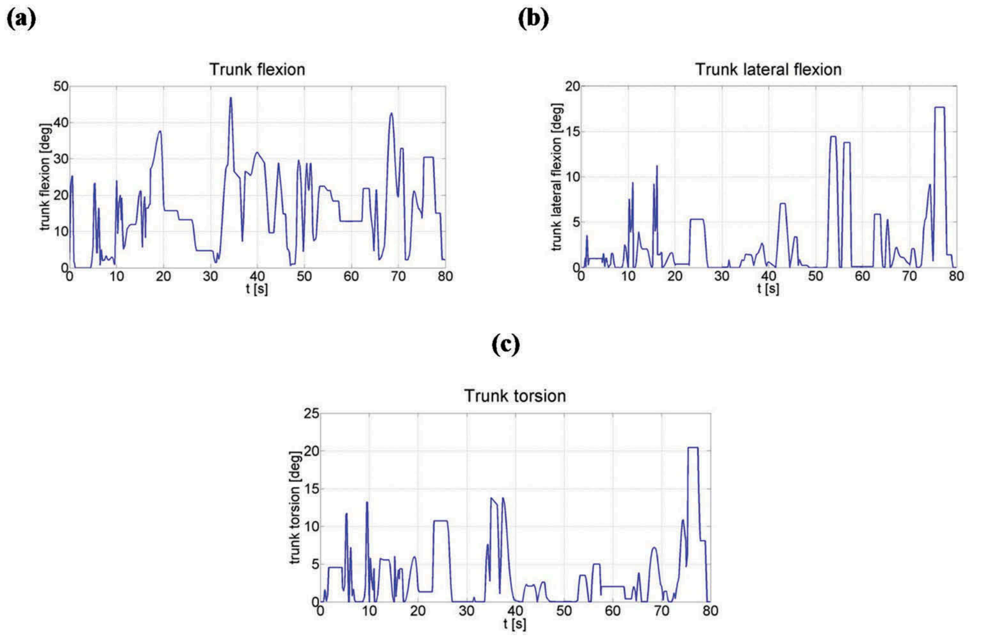


Figure 6. Test case – posture angles trends: (a) trunk flexion; (b) trunk lateral flexion; (c) trunk torsion.

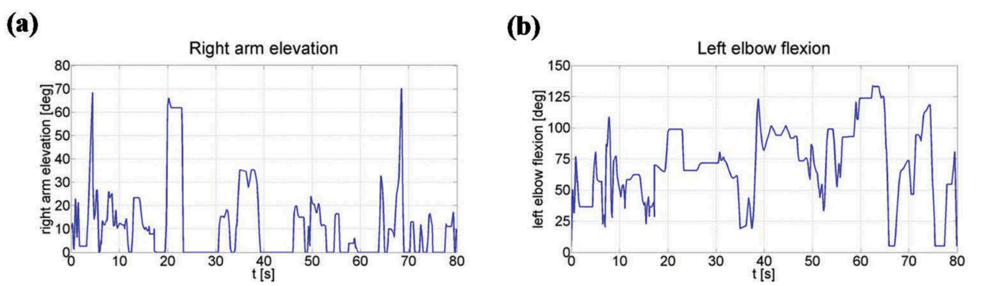


Figure 7. Test case – posture angles trends: (a) right arm elevation; (b) right elbow flexion.

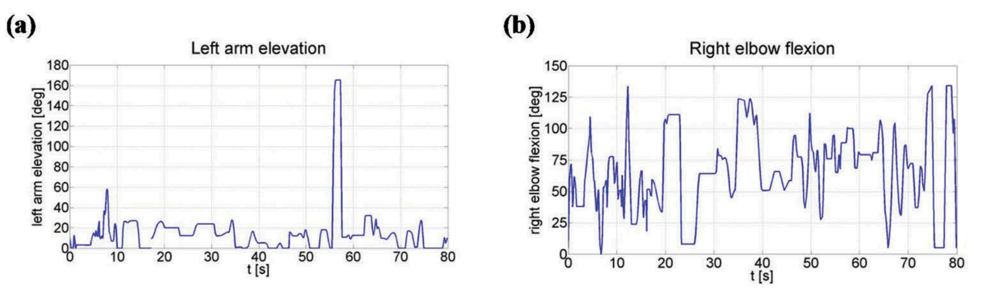


Figure 8. Test Case – Posture angles trends: (a) left arm elevation; (b) left elbow flexion.

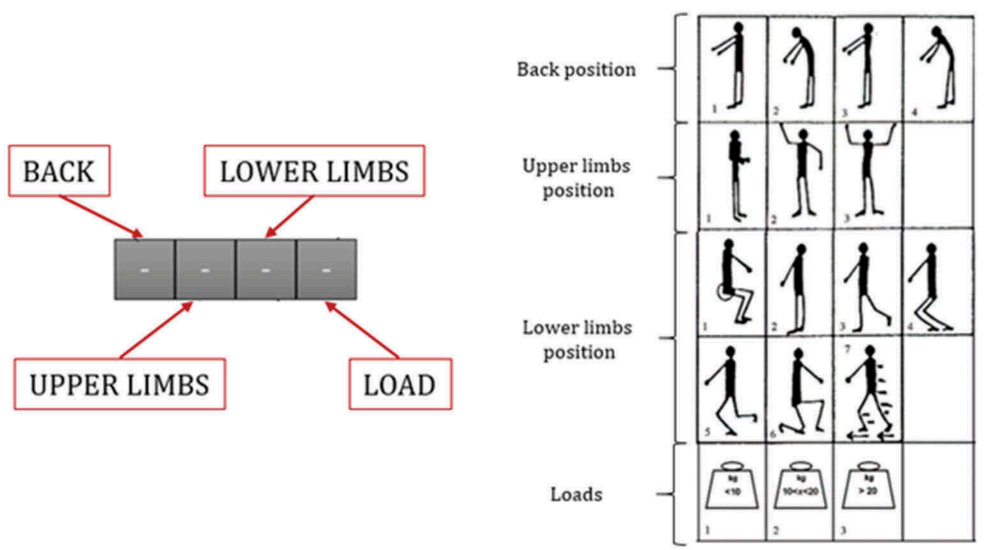


Figure 9. OWAS code.

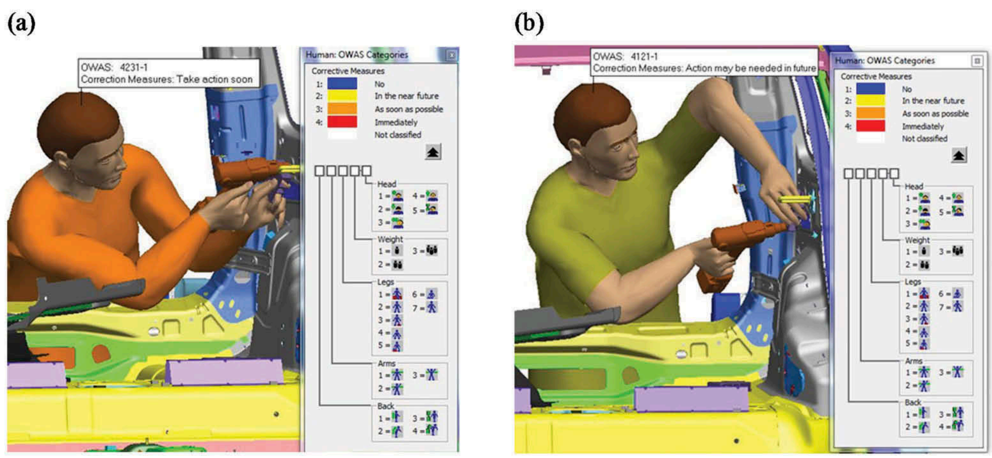


Figure 10. Postures assumed during screwings evaluated by OWAS.

The OWAS Risk Index is evaluated by the following Equation 1:

$$RI_{OWAS} = (a \times 1 + b \times 2 + c \times 3 + d \times 4) \times 100 \qquad (1)$$

By applying Equation (1), the risk index value is equal to:

$$RI_{OWAS} = 170,5$$

The score is within the low-risk area.

Table 6. Postures analysed by OWAS analysis tool.

Working postures analysis by OWAS			
Number of observed postures		58	
Class of risk	Number of postures	Percentage frequency	
1	19	a	33 %
2	37	b	63,5 %
3	2	c	3,5 %
4	0	d	0

3.2. Forces

The 'Force Solver' tool, integrated in Tecnomatix Process Simulate software, enables to analyse the maximum force that a human model can exert in a posture. It allows specifying the posture and all input parameters. The analysis provides the maximum allowable force along a specified direction.

In addition, it is possible specifying the frequency for repetitive tasks that influences the maximum acceptable strength. For this task, a reduction in maximum strength capability is observed, as suggested in (Potvin, 2012).

The SOP suggests the forces to be exerted by the worker during the assembly operations. The activity consists of several applications of forces of about 5 N (interlocks, pressing the actuation button of the screwdrivers), a low value that does not require ergonomic evaluation.

The evaluation shall be performed for the counter-reaction forces of tightening end that the worker needs to exert in a certain direction that depend on the geometry of the resource, the tightening torque and the assumed posture.

Using the 'Force solver' tools of Tecnomatix Process Simulate® software, it is possible evaluating the maximum force that the worker can exert during the screwing activities, number 7 (Connect rear window ground) and number 14 (place audio unit and perform two screwings) of Table 3.

About activity 7, considering the geometry of screwdriver #1 (Figure 11) and the 3 *Nm* tightening torque (T), according to Equation 2, the reaction force of tightening end is:

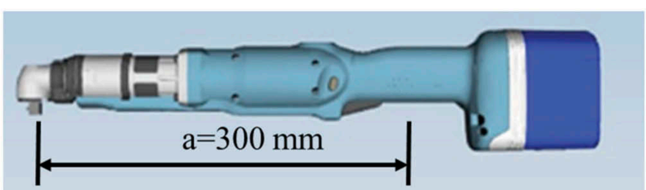


Figure 11. Geometry of screwdriver #1.

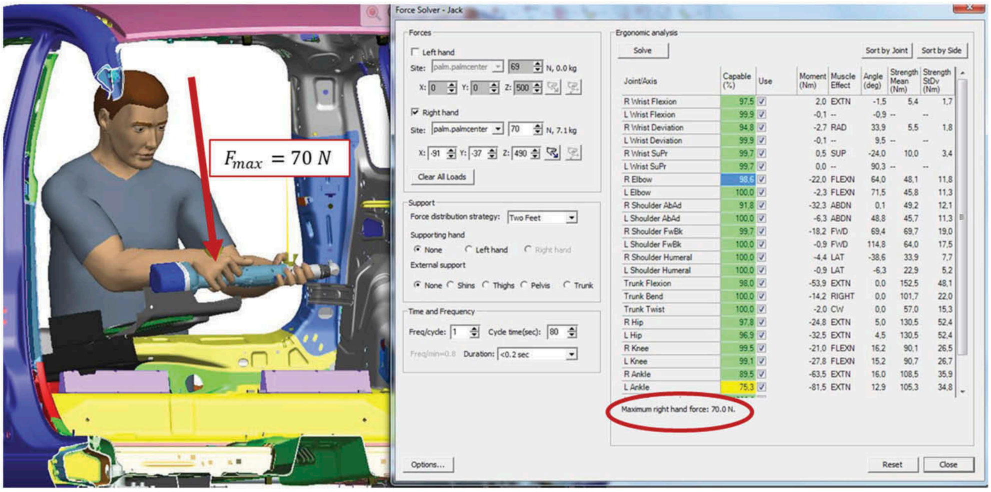


Figure 12. Maximum applicable force for task number 7, evaluated by 'force solver' tool.

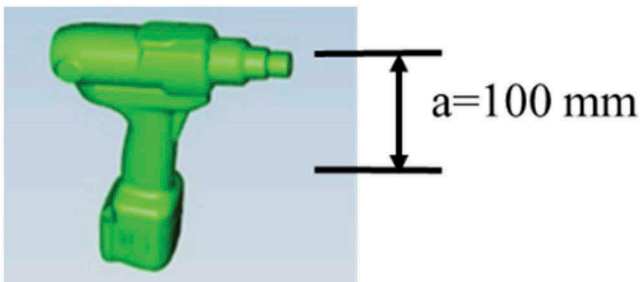


Figure 13. Geometry of screwdriver #2.

$$F_r = \frac{T_{\#1}}{a} = \frac{3Nm}{0.3m} = 10\ N \tag{2}$$

The 'force solver' tool suggests a maximum applicable force of 70 N, as shown in Figure 12, that means the operation is ergonomically compliant.

About activity 14, considering the geometry of screwdriver #2 (Figure 13) and the 3 *Nm* tightening torque (T), the reaction force, according to Equation 3, of tightening end is:

$$F_r = \frac{T_{\#2}}{a} = \frac{3Nm}{0.1m} = 30\ N \tag{3}$$

The 'force solver' tool suggests a maximum applicable force of 35 N, as shown in Figure 14, that means the operation is ergonomically compliant.

3.3. Manual handling

The investigated assembly activity does not consider lifting actions because of the weight of the handled loads, but just a pushing action, evaluated by Snook & Ciriello protocol.

The risk index (RI) is evaluated by the following Equation 4:

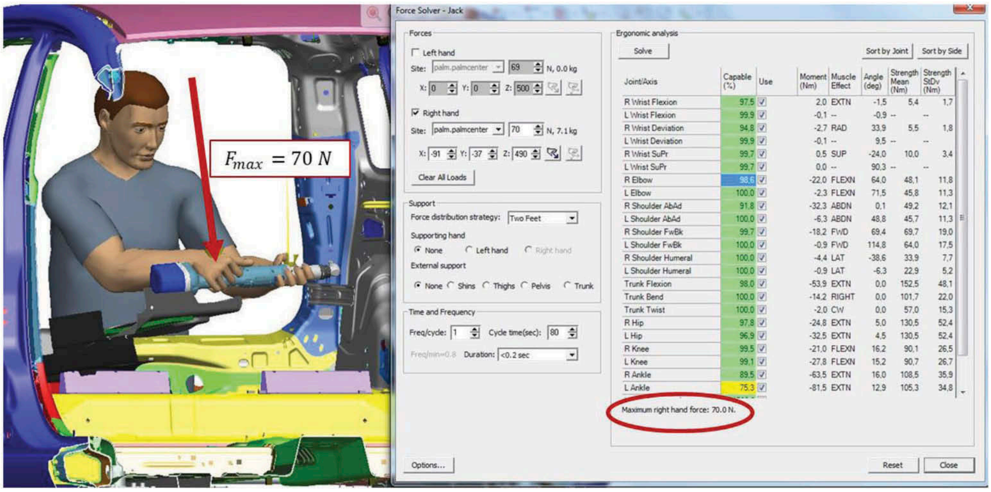


Figure 14. Maximum applicable force for task number 14, evaluated by 'force solver' tool.

$$RI = \frac{W_T}{W_R} \tag{4}$$

where W_T is the transported weight and $W_R$is the recommended weight.

The recommended limits, in terms of maximum initial (IF) and maximum sustained (SF) forces in kgf, are determined from the table for *maximum acceptable force of push for male*.

Geometrical (distances) and physical (durations) data can be extracted from the simulation and, knowing the physical properties of the floor, it is possible to evaluate the initial and the sustained forces (in N) exerted by the worker by the Equations 5 and 6, neglecting the friction forces between bearing and wheel hub and between pivot and wheel.

$$IF = m \cdot a + F_{sf} \tag{5}$$

$$SF = F_{df} \tag{6}$$

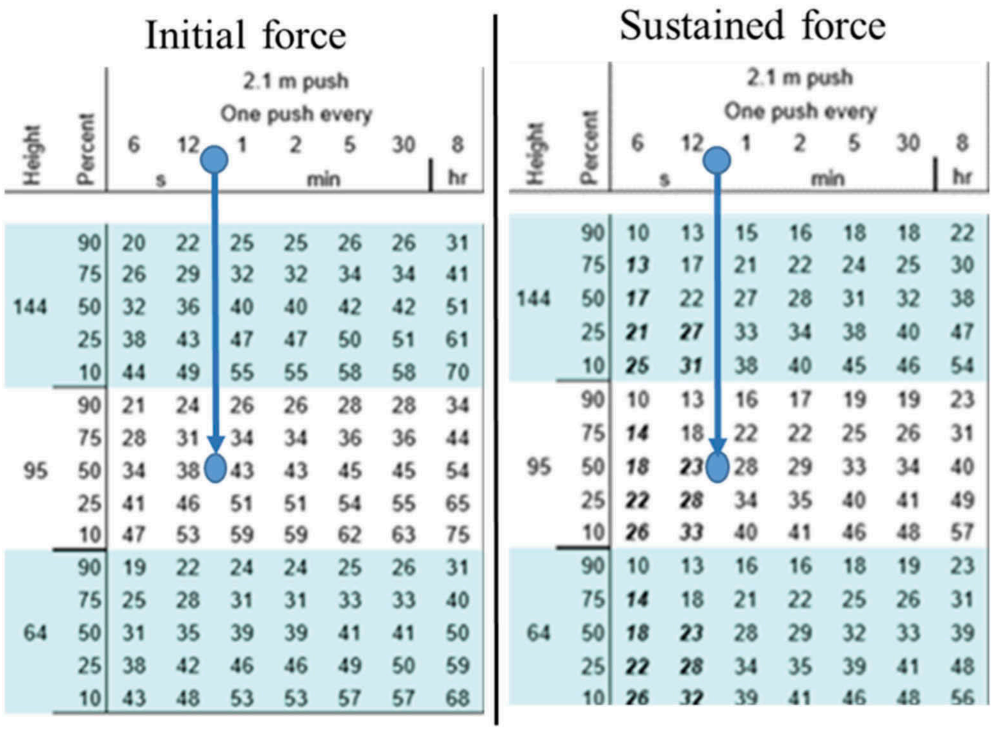
where m is the total mass of the cart, a is the acceleration impressed to the cart, F_{sf} is the static friction force and F_{df} is the dynamic friction force, dependent on static (μ_s) and dynamic (μ_d) friction coefficients, respectively. These values have been provided by the Company and they are reserved.

About pushing action, the covered distance and the accelerations can be measured from the simulation.

In this case, the covered distance d is 4300 mm (Figure 5(c)).

Considering the total mass m of the cart, an initial acceleration of 0.4 m/s^2, typical for the pushing/pulling carts activity in an automotive plant, the wheel deflection angles of 90° with respect to the direction of push (the worst case) and the static (μ_s) and dynamic (μ_d) friction coefficients it is possible to determine the initial and the sustained forces, according to Equations 6 and 7:

$$IF = 18.54\ N \sim 19\ N \tag{7}$$



Initial force

2.1 m push — One push every

Height	Percent	6 s	12 s	1 min	2 min	5 min	30 min	8 hr
144	90	20	22	25	25	26	26	31
	75	26	29	32	32	34	34	41
	50	32	36	40	40	42	42	51
	25	38	43	47	47	50	51	61
	10	44	49	55	55	58	58	70
95	90	21	24	26	26	28	28	34
	75	28	31	34	34	36	36	44
	50	34	38	43	43	45	45	54
	25	41	46	51	51	54	55	65
	10	47	53	59	59	62	63	75
64	90	19	22	24	24	25	26	31
	75	25	28	31	31	33	33	40
	50	31	35	39	39	41	41	50
	25	38	42	46	46	49	50	59
	10	43	48	53	53	57	57	68

Sustained force

2.1 m push — One push every

Height	Percent	6 s	12 s	1 min	2 min	5 min	30 min	8 hr
144	90	10	13	15	16	18	18	22
	75	13	17	21	22	24	25	30
	50	17	22	27	28	31	32	38
	25	21	27	33	34	38	40	47
	10	25	31	38	40	45	46	54
95	90	10	13	16	17	19	19	23
	75	14	18	22	22	25	26	31
	50	18	23	28	29	33	34	40
	25	22	28	34	35	40	41	49
	10	26	33	40	41	46	48	57
64	90	10	13	16	16	18	19	23
	75	14	18	21	22	25	26	31
	50	18	23	28	29	32	33	39
	25	22	28	34	35	39	41	48
	10	26	32	39	41	46	48	56

Figure 15. Evaluation of FI and SF, in kgf, from Snook & Ciriello table for pushing.

$$SF = 1.54\ N \sim 1.6\ N \tag{8}$$

To extract the values from Snook & Ciriello table (Figure 15), it is necessary tuning the covered distance according to frequency. In this case, 4.3 m in 80 s become 2.1 m in 40 s.

By applying a linear interpolation and by using Equation 6, the recommended values of initial and sustained forces, in N, are:

$$IF_R = 510\ N$$

$$SF_R = 260\ N$$

The Risk Indexes (RI) for IF and SF, from Equation 4 are:

$$RI_{IF} = \frac{IF}{IF_R} = \frac{19\ N}{510\ N} = 0.037$$

$$RI_{SF} = \frac{SF}{SF_R} = \frac{1.6\ N}{260\ N} = 0.0061$$

The highest value between RI_{IF} and RI_{SF} is within the low-risk area. Hence, it is possible to consider the pushing activity ergonomically compliant.

3.4. Repetitive actions with upper limbs

The repetition of an activity induces stress, small traumas and wear of joints, muscles and tendons, which gradually cause pathologies in the affected districts over a more or less long time (months or years).

For the evaluation of occupational risk factors affecting musculoskeletal disorders in the upper limbs, the High-Precision OCRA Checklist has been used for the calculation of a synthetic index of exposure to repetitive movements of the upper limbs.

The tables below show the evaluation of factors and multipliers scores necessary to calculate the Risk Index (Equation 9) for OCRA checklist.

Table 7 shows the characteristics of shift the job description, provided by the responsible of the plant, necessary to evaluate the recovery (RM) and the duration (DM) multipliers. The value of RM is greater than 1 because there are not sufficiently long recovery times during the cycle (2.5 s of passive time).

By observing the simulation, it is possible to count the technical actions (static and dynamic) to evaluate the frequency score (Table 8).

The awkward postures (Table 9) have been evaluated by analysing the trends over the time of shoulder (Figures 7(a) and 8(a)), elbow (Figures 7(b), 8(b) and 16(a,b)) and wrist (Figures 17 and 18) postural angles, as well as done in 3.1.1 for working postures of whole body.

Table 7. Evaluation of recovery and duration multipliers.

Synthesis of net length of repetitive task within average working day			
Gross shift length	480 min	Net shift length	480 min
NO of breaks effective for recovery within shift		3	
Total breaks length (excluding lunch)		30 min	
Lunch break length		30 min	
Repetitive Job description			
NO of pieces/worker/shift	315	Average net shift length	420 min
Cycle time	80 s	Average net duration, in shift, repetitive work	420 min
Total seconds of observed average active time in the cycle	77.5 s	Net cycle length	80 s
Total seconds of observed average passive time in the cycle	2.5 s	Active time duration in a cycle	77.5 s
Hours without sufficient recovery		3	
Results			
Recovery Multiplier – RM			**1.20**
Duration Multiplier – DM			**0.95**

Table 8. Evaluation of frequency score for right and left limbs.

Main risk factor assessment and identification of priority for improvement					
Right			Left		
Dynamic actions	No. of actions	Frequency	Dynamic actions	No. of actions	Frequency
	36	27		33	24.8
Static actions	-		Static actions	-	
Results					
Frequency score - FrS		**0.5**	Frequency score - FrS		**0.5**

Table 9. Evaluation of awkward posture score for right and left limbs.

Upper Limbs Awkward Postures					
Right			Left		
	Duration [s]	% cycle		Duration [s]	% cycle
Hand grasp in pinch or hook or palmer	3	4	Hand grasp in pinch or hook or palmer	7	8
Arm almost at shoulder height	0	0	Arm almost at shoulder height	1.6	2
Extreme wrist deviation in flexion and/or radius/ulnar deviation	29	36	Extreme wrist deviation in flexion and/or radius/ulnar deviation	25	31
Complete rotation of goods and/or wide elbow flexion/extension	45	56	Complete rotation of goods and/or wide elbow flexion/extension	57	71
Stereotype	NO		Stereotype	NO	
Results					
Posture score - PS		**4.5**	Posture score - PS		**6.5**

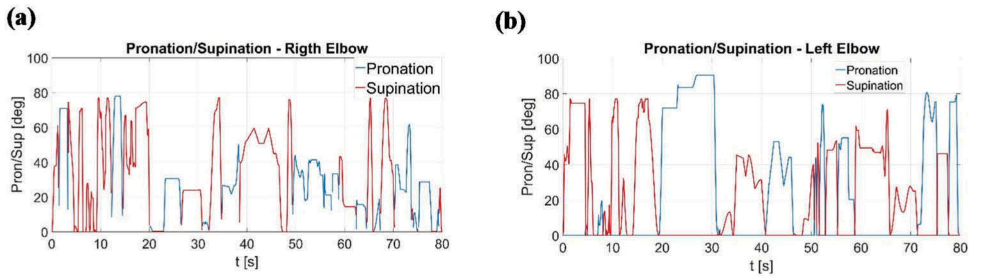


Figure 16. Right (a) and left (b) elbows pronation/supination angles.

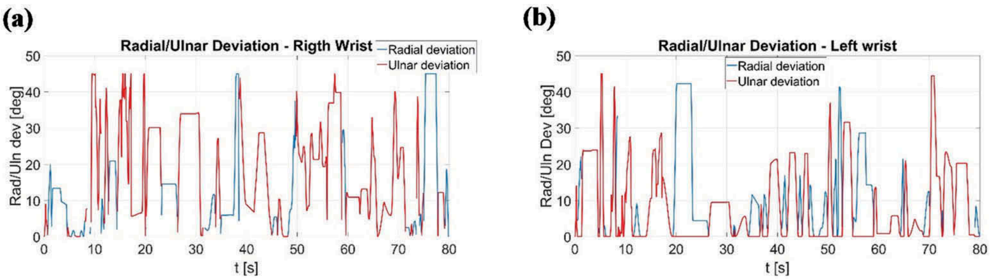


Figure 17. Right (a) and left (b) wrists Radial/Ulnar deviation angles.

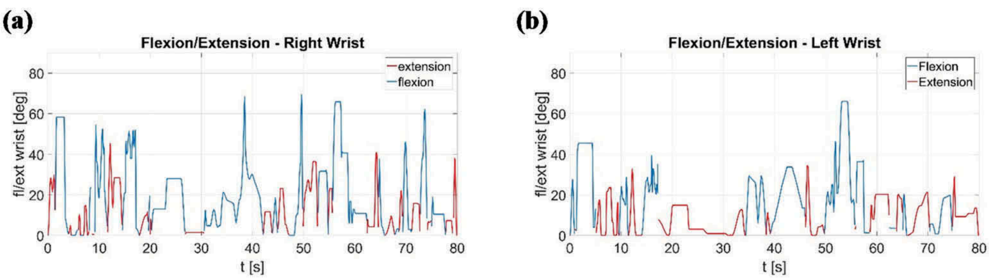


Figure 18. Right (a) and left (b) wrists flexion-extension angles.

From the trends above, it is possible to note that, especially about elbow pronation and supination, the angles reach high values and durations, which indicate that the wrist assumes awkward postures, analysed in detail in Table 9.

The scores of exerted forces (Table 10) have been evaluated considering the values of forces calculated in 3.2 about the use of screwdrivers and the other values of forces suggested by SOP. All the forces exerted in this activity, at most can be considered moderate.

The additional score (Table 11) is due to the characteristic of the assembly line, which imposes the rhythm of work.

The synthetic index of exposure (Risk Index) is done by the following Equation (9):

$$R.I. = (FrS + PS + FoS + AS) \times RM \times DM \tag{9}$$

Table 10. Evaluation of force score for right and left limbs.

Force exertion					
Right			Left		
Moderate force (Borg scale 3-4) using tools or doing any other working task	Duration [s]	% cycle	Moderate force (Borg scale 3-4) using tools or doing any other working task	Duration [s]	% cycle
	10	13		3	10
Results					
Force score - FoS		**0.5**	Force score - FoS		**0**

Table 11. Evaluation of additional score.

Additional factors	
Line rate imposed by machinery	Modulation not allowed: pace completely determined by machinery
Results	
Additional score –AS	**2**

Table 12. Total score of OCRA checklist R.I.

OCRA Checklist R.I. Final Score	
RIGHT	**9.12**
LEFT	**10.26**

Table 12 shows the final scores for right and left limbs. Both scores fall into the very low-risk area, and the left limb is the most stressed during the activity.

3.5. Discussion

Regarding this test case, the risk indexes values, according to Table 2, are summarised in Table 13:

According to the workflow, being all the four indexes within the 'low-risk area', it is possible to exit from the iteration. The decision-making process, in this case, would have validated the design.

Table 13. Risk indexes: results.

Working Postures	Forces	Manual Material Handling	Repetitive Actions with upper limbs
170.5	Exerted forces less than the maximum applicable force	**0.037** (Initial Force) **0.0061** (Sustained force)	**10.26** (left limb)
Low risk	Low risk	Low risk	Very low risk

The risk indexes do not reach critical values, and the workplace can be considered ergonomically safe.

The high number of numerical data and the detailed analyses of the main involved physical human factors proved their useful to test the product assembly feasibility.

Once the iteration is completed and, after eventual design changes, the design has been numerically validated, for definitively validating the workplace design, according to Digital Manufacturing strategy, it is possible to perform a rapid physical simulation in which a worker reproduces the working task in a laboratory and the ergonomists can assess the ergonomic indexes experimentally.

The same case study has been carried out in (Caputo et al., 2019), where the EAWS scores have been evaluated. About these last, the EAWS scores related to the working postures, exerted forces and manual material handling are within the low-risk area, while the EAWS score related to repetitive actions is within the medium risk area. Even if the anthropometry of the used DHMs is slightly different, it is possible to compare the results achieved in this paper with the EAWS ones that are in agreement about the working postures, the exerted forces and the manual material handling, while are in slight disagreement about the repetitive actions, since for EAWS score the most stressed limb is the right one, while for OCRA is the left one. In addition to different approach between OCRA checklist and EAWS section 4, the difference is due to the fact that according to OCRA score the left limb is more stressed due to incongruous postures of elbow and shoulder, although the workload on the right limb is higher. This aspect will need further investigation, starting with the improvement of the numerical model.

4. Conclusions

A preventive performance evaluation of workplaces design is a formidable task to test the product feasibility since the design phase of a new product, giving the opportunity to reduce time and costs and the possibility to change design parameters without risks.

Simulating operating tasks in a virtual environment provides a high number of data, useful to test the product feasibility based on ergonomic indexes.

The procedure proposed by this research, starting from a preliminary design of the workplace, allows validating its ergonomic performances by evaluating the desired ergonomic indexes in a virtual environment.

In order to validate the proposed method, a real test case, selected by analysing the assembly lines of FCA *Gianbattista Vico Plant*, has been analysed, showing how a large amount of numerical data allows an exhaustive evaluation of ergonomic indexes.

The aim of the research is to show the efficacy and potential that a numerical ergonomic evaluation method can offer.

This means that, in developing new product in the automotive sector (and in all other manufacturing industries that use assembly line organisation), the proposed procedure is ready to be applied and to give support to ergonomists and designers for a human-centred factory design, combining the expertise of ergonomics specialists with the advantages provided by virtual simulations and numerical data. This latter aspect would make it suitable for the design phase, with a significant reduction in costs for the implementation phase and an improvement in the working conditions of the operators, who will immediately have available a workstation of which ergonomic efficiency has been previously validated.

Another important aspect can be represented by the use of virtual simulation as a training tool for workers, in order to ensure the proper execution of the task.

Further development can interest the use of wearable devices, specially motion capture systems and cyber gloves, as immersive reality tools with the aim to realise simulations that are more realistic.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Abdullah, T. A., Popplewell, K., & Page, C. J. (2003). A review of the support tools for the process of assembly method selection and assembly planning. *International Journal of Production Research*, *41*(11), 2391–2410.

Alkan, B., Vera, D., Ahmad, M., Ahmad, B., & Harrison, R. (2016). A lightweight approach for human factors assessment in virtual assembly design: An evaluation model for postural risk and metabolic workload. *Procedia CIRP*, *44*, 26–31.

Baraldi, E. C., & Kaminski, P. C. (2011). Ergonomic planned supply in an automotive assembly line. *Human Factors and Ergonomics in Manufacturing & Service Industries*, *21*(1), 104–109.

Brandl, C., Mertens, A., & Schlicl, C. (2017). Effect of sampling interval on the reliability of ergonomic analysis using the Ovako working posture analysis system. *International Journal of Industrial Ergonomics*.
Caputo, F., Greco, A., D'Amato, E., Notaro, I., & Spada, S. (2018). A preventive ergonomic approach based on virtual and immersive reality. *Advances in Intelligent Systems and Computing*, *588*, 3–15.
Caputo, F., Greco, A., Fera, M., & Macchiaroli, R. (2019). Digital twins to enhance the integration of ergonomics in the workplace design. *International Journal of Industrial Ergonomics*, *71*, 20–31.
Caragnano, G., & Lavatelli, I. (2012). ERGO-MTM model: An integrated approach to set working times based upon standardized working performance and controlled biomechanical load. *Work*, *41*, 4422–4427.
Chryssolouris, G. (2008). Digital manufacturing: History, perspective and outlook. *Journal of Engineering Manufacturing*.
Colombini, D., Occhipinti, E., & Alvarez-Casado, E. (2013). *The revised OCRA checklist method* (1st ed.). Barcelona: Editorial Factors Human.
COU89. (1989). Council directive 89/391/EEC of June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work.
Das, B., Shikdar, A. A., & Winters, T. (2007). Workstation redesign for a repetitive drill press operation: A combined work design and ergonomic approach. *Human Factors and Ergonomics in Manufacturing*, *17*(4), 395–410.
Demirel, H. O., & Duffy, V. G. (2007). Applications of digital human modeling in industry. *Lecture Notes in Computer Science*, 4561.
DIR06. (2006). DIRECTIVE 2006/42/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 17 May 2006 on machinery and amending directive 95/16/EC (recast.).
Dul, J., & Neumann, P. (2009). Ergonomic contributions to company strategies. *Applied Ergonomics*, *40*, 745–752.
Falk, A. C., & Rosenquist, M. (2014). A model for calculation of the costs of poor assembly ergonomics (part 1). *International Journal of Industrial Ergonomics*, *44*, 140–147.
Freivalds, A., & Niebel, B. (2014). *Niebel's methods, standards and work design*. McGraw-Hill Higher Learning.
Glaeser, D., Fritzsche, L., Bauer, S., & Sylaja, V. J. (2016). Ergonomic assessment for DHM simulation facilitated by sensor data. *Procedia CIRP*, *41*, 702–705.
Gordon, C. C., Bradtmiller, B., Parham, J. L., Barrientos, P., Paquette, S. P., & Muncher, M. (2014). *Anthropometric survey of US Army personnel: Method and summary statistics*.
Groover, M. P. (2014). *Work systems: The methods, measurement and management of work*. Upple Saddle River, NJ: Pearson Prentice Hall.
Hignett, S., & McAtamney, L. (2000). Rapid entire body assessment (REBA). *Applied Ergonomics*, *31*(2), 201–205.
Hovanec, M., Korba, P., & Solc, M. (2015). *Tecnomatix for succesful application in the area of simulation manufacturing and ergonomics*. Albena.
ISO. (2000). ISO 11226: Ergonomics -evaluation of static working postures.
ISO. (2003). ISO 11228-1: Ergonomics - manual handling - part 1: Lifting and carrying.
ISO. (2006). ISO 11228-2: Ergonomics - manual handling - part 2: Pushing and pulling.
ISO. (2007). ISO 11228-3: Ergonomics - manual handling - part 3: Handling of low loads at high frequency.
ISO. (2014). ISO 12295: Ergonomics — application document for international standards on manual handling (ISO 11228-1, ISO 11228-2, ISO 11228-3) and evaluation of static working postures (ISO 11226).
Kharu, O., Kansi, P., & Kuorinka, I. (1977). Correcting working postures in industry: A practical method for analysis. *Applied Ergonomics*, *8*(4), 199–201.
Kuehn, W. (2006). Digital factory - Integration of simulation enhancing the product and production process towards operative control and optimization. *International Journal of Simulation*, *7*(7).

Lawson, G., Salanistri, D., & Waterfield, B. (2016). Future directions for the development of virtual reality within an automotive manufacturer. *Applied Ergonomics*, *53*, 323–330.
Makarova, I., Khabibullin, R., Belyaev, E., Mavrin, V., & Verkin, E., (2015). Creating a safe working environment vi analyzing the ergonomics parameters of workplaces on an assembly conveyor. Proceedings of IEEE IESM 2015 (pp. 947–954). Seville, Article number 7380269.
Maynard, H. B., Stegemerten, G. J., & Schwab, J. L. (1948). *Methods-time measurement*. N.Y.: McGraw-Hill.
NASA. (1987). Man-system integration standards (NASA-STD-3000).
Poirson, E., & Delangle, M. (2013). *Comparative analysis of human modeling tools*. United States: Ann Arbor.
Potvin, J. R. (2012). Predicting maximum acceptable efforts for repetitive tasks: An equation based on duty cycle. *Human Factors: the Journal of the Human Factors and Ergonomics Society*, *54*(2), 175–188.
Schaub, K., Caragnano, G., Britzke, B., & Bruder, R. (2012, January). The European assembly worksheet. *Volume Theoretical Issues in Ergonomics Science*.
Siemens PLM Software Inc. (2017). Tecnomatix eMServer platform 13.1.1 help.
Snook, S. H., & Ciriello, V. M. (1991). The design of manual handling tasks: Revised tables of maximum acceptable weights and forces. *Ergonomics*, *34*(9), 1197–1213.
Spada, S., Germanà, D., Sessa, F., & Ghibaudo, L. (2015, August 9–14). FCA ergonomics approach in developing new cars: Virtual simulation and physical validation. Proceedings 19th Triennial Congress of the IEA, Melbourne.
Stephens, A., & Godin, C. (2006). *The trick that Jack built: Digital human models and their role in the design of work cells and product design*. SAE Technical Paper.
Sun, X., Houssin, R., Renaud, J., & Gardoni, M. (2018). Towards a human factors and ergonomics integration framework in the early product design phase: Function-task-behaviour. *International Journal of Production Research*, *56*(14), 4941–4953.
Takala, E. P., Pehkonen, I., Mikael, F., Hansson, G. A., Mathiassen, S. E., Neumann, W., … Winkel, J. (2010). Systematic evaluation of observational methods assessing biomechanical exposures at work. *Scandinavian Journal of Work, Environment & Health*, *36*(1), 3–24.
Vitiello, M., Galante, L., Capoccia, M., & Caragnano, G. (2012). Ergonomics and workplace design: Application of ergo-UAS system in Fiat Group Automobiles. *Work*, *41*, 4445–4449.
Waters, T. R., Putz-Anderson, V., Garg, A., & Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Journal Ergonomics*, *36*, 749–776.