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An automatic procedure based on virtual ergonomic analysis to promote human-centric manufacturing

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Abstract

Today manufacturing enterprises aim not only to deliver high-value, cost-effectively products in a sustainable way, but also to consider the quality of the working environments. The analysis of human factors, which strongly affect time and quality of manufacturing processes, are crucial for satisfying people involved in the manufacturing process and making them safe, preventing diseases, errors and excessive workload. The paper presents a structured procedure to automatically extract data from virtual analysis made by digital manufacturing tools and measure a set of indicators to validly assess manufacturing ergonomics. The research considers the state of the art in manufacturing ergonomics and defines a set of indicators suitable for manufacturing manual operations, focusing on assembly tasks. Furthermore, it defines a methodology to automatically extract data valorising the selected indicators and an application, based on Visual Basic, to generate the specific task list and related assessment. The result is a rapid and objective assessment, independent from the experience of the user, which can be executed during process design. The procedure has been applied to an industrial case study, where the manual assembly of cabin supports on the tractor chassis has been analysed in order to correct the most uncomfortable steps and obtain a more ergonomic process. A decrease of the EAWS score, calculated with the proposed method, allowed to validate the proposed solution, suggesting a redesign of the assembly cycle to improve the working conditions. Such a procedure anticipates the analysis of the workers' wellbeing during the design stage to support the definition of human-centric manufacturing processes, simplifying and accelerating the assessment activities.

Keywords: Manufacturing Ergonomics, Digital Manufacturing, Human Factors, Human-Centered Design (HCD), Virtual Engineering

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1. Introduction

Although the fourth industrial revolution is evolving at an exponential pace, transforming entire systems of production, management, and governance, sustainability of industrial workspaces and workers' ergonomics are assuming growing importance. Indeed, also in modern industries manual operations in manufacturing and assembly tasks still represent a significant portion of the production process [1]. The main aspects to be faced by the social innovation include preventive occupational health and safety, human-centered design of work, employee participation, and work-life balance. Human-focused best practices have to be defined and implemented to solve existing criticalities from an ergonomics perspective and increase the operators' wellbeing. Monitoring key parameters and consequently adapting tasks, workstations, tools, and equipment to fit the worker, helps reducing physical work-related disorders and stress. Indeed, it is known that the quality of life and the quality of production are both strongly dependent on the quality of the working environment [2], which influences the workers' health, safety, and performance. Evidences from literature demonstrated that adopting ergonomics during the workspace design has benefits in terms of productivity and comfort, and highlighted how participatory approaches contribute to success [3]. Although the importance of both operational performance and employee wellbeing for organizational success are intuitive, organizations often perceive a conflict between them, mainly due to the lack of standards and practical procedures to easily adopt human-centric approaches and promote ergonomics [4]. In this scenario, a specific set of standards and regulations is required in order to guarantee safe and health conditions of the workers and avoid work-related musculoskeletal disorders [5]. However, they are not enough to effectively promote a preventive ergonomic approach during workspace design: ergonomic experts are usually called to verify the situation when the process is already running, on the basis of checklists, completed by hand after user observation. Recently, digital approaches are available and can be successfully applied to simulate the workers actions [6]. In this direction, the paper proposes the adoption of digital tools to anticipate ergonomic analysis during process design in terms of layouts and tasks, and defines a structured procedure to automatically extract data from the virtual analysis and measure a set of indicators to validly assess manufacturing ergonomics. The research goal is to define and validate a new ergonomic method based on virtual analysis to support the workstation layout design compliant with the EAWS (Ergonomic Assessment Work-Sheet) model. It aims at overcoming the limits of the traditional EAWS use. Indeed, traditionally, once the working space and the task list are defined, an EAWS form has to be manually by expert filled in order to provide a consumptive assessment. However, human postures for each task and subtask are difficult to estimate by experts, and body dimensions can be difficult to measure. Moreover, all the information has to be inserted manually; this is very time consuming and strongly subjective, and difficultly replicable.

2. Research background

The most relevant standards about work-related musculoskeletal risks in manual operations are represented by the international UNI 11228 and the European EN 1005. These standards are divided in different sections focusing on different activities that affect the health of the operator. The first section (EN 1005-2) deals with limits for manual lifting and carrying of objects, considering several aspects of the performed task as its intensity, frequency and duration, and establishes the relations between them. Then, EN 1005-3 deals with pushing and pulling of objects, EN 1005-5 with by handling low loads at high frequency [7] and EN 1005-4 with the postures assumed by the operator. In order to get an overall evaluation of the different risk areas and to concentrate all the efforts on a rapid redesign, a first level ergonomic tool based on the standards is needed. In this context, the EAWS (Ergonomic Assessment Work-Sheet) method has been recently developed to provide a synthetic overall assessment by gathering the various biomechanical loads affecting the workers in an only scale [8]. It aims to provide a first level risk evaluation, in which a quick screening checklist is required due to biomechanical overload. The overall score includes any biomechanical risk to which the operator may be exposed during a working task. Such a method has been conceived starting from the Automotive Assembly Work Sheet (AAWS), in order to satisfy all the UNI EN 1005 parts and the corresponding ISO standards (11226 and 11228). It can be applied to satisfy different types of industries, from large-scale production to custom-made production. It allows a set of advantages for industrial use: the differences between the score generated by two different applicators for the same working task are minimized, because of homogeneous documentation; it supports the preliminary design phase of the workstation (not only the evaluation); it's applicable to a wide range of fields, from big automotive factories (short and repetitive cycles) to custom productions (long cycles), thanks to the integration of different regulations. Up to a certain extent, EAWS can also be used as the second level analysis tool, since it is quite analytical and detailed; indeed, EAWS gives the necessary information to redesign the work task, making the second level systems seldom necessary. However, a set of more detailed and specific tools are defined and used on the basis of the first level risk assessment. Depending on the critical areas (e.g. body posture, action forces, manual material handling, upper limb load and repetitive tasks) the most appropriate tool is adopted. Table 1 synthetizes the tools with respect to risk areas and reference standards.

EAWS is structured in four sections, each of them covering a specific risk area: Body Postures, Action forces, Manual Materials Handling and Upper Limbs in repetitive tasks. EAWS provides one score for each working cycle, which is exposed in a traffic light scheme (green, yellow, red) according to the Machinery Directive 2006/42/EC:

- **0-25 points (green)**: no risks or low risk = no action is needed;
- **>25-50 points (yellow)**: possible risk = redesign if possible, take other measures to control the task;
- **>50 point (red): high risk** = take actions to lower the risk.

Table 1: Overview of the most common ergonomic tools used in industry

	Standard		Tools	
Risk Areas	**CEN**	**ISO**	**2nd Level**	**1st Level**
Body Postures	1005-4	11226	WAS	EAWS
Action Forces	1005-3	11228-2	NOOK-CIRIELLO STRAIN INDEX	
Manual Material Handling	1005-2	11228-1	IO	

Upper limb load in repetitive tasks	1005-5	11228-3	SH CRAINDEX		

3. The research approach

The research adopts a virtual approach to create a preventive ergonomic assessment of the workstation layout and the working cycle using digital manufacturing tools. In particular, the research uses an advanced VBA-coded Excel sheet, and Human Modelling software (i.e. Siemens Jack). The working cycle with its tasks and subtasks is initially modelled within the virtual scene by the Human Modelling software toolkit. It is usually done before the creation of the real workstation, in order to design and verify the layout. The postures assumed by the operator are simulated by the use of virtual mannequins, step by step. The creation of postures can be made in a manual way, by placing the manikin in the virtual scenario, or by using a Motion Capture system [9].

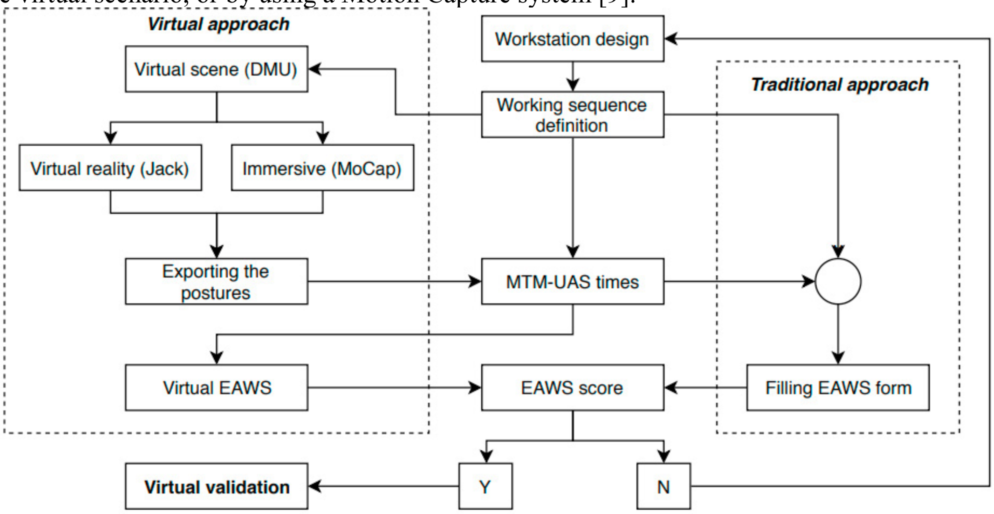


Figure 1: The research approach and workflow.

At this point, the single postures are automatically exported on the Excel sheet, recognized and classified, by an ad-hoc automatic routine. Once the postures are exported, the list of tasks and related postures is automatically created into the Excel with the extracted data, and a specific EAWS form is automatically generated for the working cycle under assessment. The MTM-UAS method is used to estimate the duration of each working subtask. Once the worksheet is fully compiled, the EAWS overall score is automatically calculated and available for virtual validation. Figure 1 represents the workflow. Such routines are incorporated into a unique Excel file, called EAWS-JACK Excel worksheet, because of its connection with Siemens Jack software. However, the approach is nonspecific, so that similar routines could be created also to interface with other digital simulation tools (e.g. DELMIA).

4. The EAWS-JACK Excel worksheet

The EAWS-JACK worksheet incorporates a proper VBA code to automatic dialogue with the virtual simulation in order to make the ergonomic evaluation procedure automatic ad fast, avoiding time-consuming and boring manual activities and enabling a preventive evaluation during the virtual simulation. By using this worksheet, the user can quickly calculate the EAWS score for any simulated working task sequence. Furthermore, the worksheet is able to deal with Siemens JACK 7.0 software toolkit, exporting and recognizing the postures assumed by the virtual manikin, and to rebuild them in the sheet with the possibility to make corrections and measurements of the main joint angles and body dimensions. The prerequisite is the creation of the virtual scene using the digital simulation toolkit (i.e., Siemens Jack). All postures and movements of the operators are simulated into the virtual scene; the analyst determines also the range of the body dimensions of the workers' population (i.e., reference population), set by choosing gender and percentile of the virtual mannequins. After that, the analysis is developed in three steps: 1) Exporting the postures, 2) Compiling the working cycle, and 3) EAWS analysis. The EAWS-JACK worksheet allows to analyse any working cycle through a first and second level analysis. It finally calculates the EAWS index for the entire working cycle, and all the indices defined by the standards 1005-2/3/4 for every task under investigation.

The first step is based on the creation of a list of postures assumed by workers into the Excel worksheet by exporting the postures created into the virtual scenes (Figure 2a). As a result, a list of postures is added to the worksheet as a series of sequential events. In particular, a *.post file containing all virtual posture data is generated. The routine allows reading the postures from the *.post file and creating a table containing all the joint angles for each posture imported. The human body is schematically represented by an ensemble of segments (bones) and joints (Figure 2b). The value of the joint angles represents a rotation around a single axis. Some joints can have 3 degrees of freedom (DOF) (e.g., shoulders), featured with 3 displacement values, while some joints can be simple (e.g., knees) with a single displacement value. For example, if the body part (e.g., waist) is directed along the z-axis, it is possible to rebuild the femur by multiplying the (0,0,1) vector by the 3 rotation matrices Rx, Ry, Rz of the hip joint (joint), and by the length of the femur (segment), as described by equation (1). By multiplying each body segment with the corresponding rotation matrices, it's possible to rebuild the whole skeleton .

$$\begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ l_{21} \end{bmatrix} \tag{1}$$

To fasten the export process, an existing posture can be resumed and modified order to get a new different one by little changes. This operation can be made manually, by changing the values of the exported joint angles and uploading the posture sheet, or by dragging the hands in a new position and rebuilding the posture with a VBA code that iteratively changes the values of the joint angles until the right position is reached. The former ensures the right positioning of every body segment, but is slower especially when the user has to move long and complex kinematic chains like hands; the latter is quicker but the user cannot have the direct control of the angles. A proper toolbox created by VBA code allows posture modification (Figure 2c).

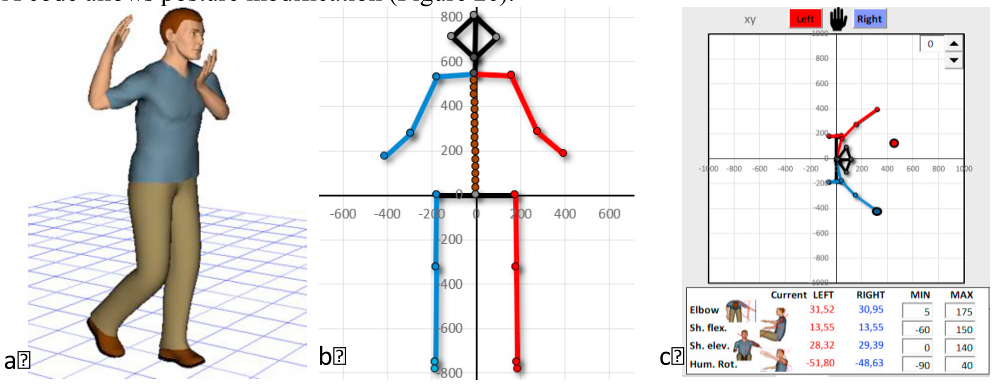


Figure 2: The posture exporting procedure - virtual mannequin (a), segmented human model (b), toolbox for posture modification (c).

The second step consists of the automatic creation of list of the working tasks by importing the posture files into the EAWS-JACK worksheet, by setting the appropriate input conditions for postures, forces and loads. A proper toolbox created by VBA code allows creating the task list through simple steps. Whenever a task is inserted, the EAWS-JACK worksheet processes the input information, automatically calculates the EN 1005 indices, and provides a summary of the task as an output (Figure 3). A traffic light scheme evaluation (red, yellow, green) is used to highlight the risk level related to the calculated indices.

Figure 3: The EAWS-JACK worksheet interface

The EAWS-JACK worksheet interface guides the user into a set of sequential actions to create the working cycle. First of all, the "General Inputs" must be specified:

- Operator Gender (this choice must be consistent with the virtual mannequin);
- Analysis Type (to be chosen between *Planning*, if the evaluation is done during the design stage, or *Observation* if data from real operators is available to create a full-size model of the machinery.

Task are then inserted by clicking of the task "Add Task", indicating:

- Task duration (with the help of the MTM-UAS method),
- Type of action,
- Starting and ending postures,
- Load information (in terms of intensity, direction, and quality of the grip).

After the creating of the working cycle, the EAWS-JACK worksheet automatically calculates the EAWS index. Furthermore, the worksheet provides the possibility to calculate the Recovery Time to bring the EAWS index below the acceptable risk limit, and to generate an output file containing all analysis data. Since the EN 1005 standards have been developed and validated mainly in non-manufacturing sectors with limited complexity, such as the food sector, a set of assumptions and simplifications have been used to adapt the standards to manufacturing and heavy-machinery production:

- The influence of an inadequate posture during the manual handling of loads is estimated using a unit frequency multiplier F_M in the risk assessment equation (ref. EN 1005-2);
- The duration multiplier m_d, relating to the cumulated duration of similar actions, is considered unitary (ref. EN 1005-3);
- The procedure is adapted to evaluate also the kneeling postures (ref. EN 1005-4);
- Postures kept for more than 4 seconds are considered as Static; otherwise are considered as Low frequency movements.

According to these assumptions, the EAWS-JACK worksheet runs a code for each sub-task, calculating the fraction of the EAWS score. Once the partials have been elaborated, the worksheet sums them and calculates the overall EAWS score. The first step is reading the posture files and estimating the relevant body dimensions, in order to classify each sub-task into a specific category. Each category is identified by a k-number (k from 1 to 18), so that a walking subtask (k=1) can be distinguished from a climbing posture (k=18). By knowing the duration and the category of each subtask, the percentage duration of each category can be calculated as by (2) and (3):

$$T^{(k)} = \sum_i T_i^{(k)} \qquad k = 1, \dots, 18 \qquad (2)$$

$$T_{\%}^{(k)} = \frac{T^{(k)}}{T_{tot}} = \frac{\sum_i T_i^{(k)}}{\sum_i T_i} \cdot 100 \qquad k = 1, \dots, 18 \qquad (3)$$

Then the Symmetric Posture Score (SPS) is calculated by (4) and (5):

$$S^{(k)} = S^{(k)}\left(T_{\%}^{(k)}\right) \qquad k = 1, \dots, 18 \qquad (4)$$

$$SPS = \sum_{k=1}^{18} S^{(k)} \tag{5}$$

where S is a linear function obtained by interpolating the values on the EAWS table. Then the Asymmetric Posture Score (APS) is calculated considering 3 factors related to the lateral bending and rotation of the trunk and the extensions of the arms, so follows:

$$S_{\alpha_2,i} = f_{I,trunk}(\alpha_2) \cdot f_{D,trunk}(T_i) \tag{6}$$

$$S_{\alpha_3,i} = f_{I,trunk}(\alpha_3) \cdot f_{D,trunk}(T_i) \tag{7}$$

$$S_{\gamma,i} = f_{I,arm}\left(max\left\{\left|\gamma_{1,dx}\right|, \left|\gamma_{2,dx}\right|, \left|\gamma_{1,sx}\right|, \left|\gamma_{2,sx}\right|\right\}\right) \cdot f_{D,arm}(T_i) \tag{8}$$

$$S_{\alpha_2} = \sum_i S_{\alpha_2,i} \qquad S_{\alpha_3} = \sum_i S_{\alpha_3,i} \qquad S_\gamma = \sum_i S_{\gamma,i} \tag{9}$$

Then the Asymmetric Posture Score (APS) is obtained by (10):

$$APS = S_{\alpha_2} + S_{\alpha_3} + S_\gamma \tag{10}$$

Finally, the Posture Score is obtained by summing APS and SPS:

$$PS = APS + SPS \tag{11}$$

In the same way, the Action Force and the Manual handling of loads sections of the EAWS form are calculated:

$$F_{\%,i} = \frac{F_i}{F_{max}} \cdot 100 \tag{12}$$

$$S_{hand,i} = g_{I,hand}\left(F_{\%,i}\right) \cdot g_{D,hand}\left(T_{\%,i}\right) \tag{13}$$

$$AFS_{hand} = \sum_i S_{hand,i} \tag{14}$$

$$S_{arm,i} = g_{I,arm}\left(F_{\%,i}\right) \cdot g_{D,arm}\left(T_{\%,i}\right) \tag{15}$$

$$AFS_{arm} = \sum_i S_{arm,i} \tag{16}$$

$$AFS = AFS_{hand} + AFS_{arm} \tag{17}$$

The Manual handling of loads is calculated as:

$$LF_i^{(r)} = l^{(r)}(M_i) \tag{18}$$

$$LF^{(r)} = \frac{\sum_i\left(LF_i^{(r)} \cdot T_i^{(r)}\right)}{\sum_i T_i^{(r)}} \tag{19}$$

The Posture Factor and the Time Factor are calculated for each r-category:

$$PF^{(r)} = \frac{\sum_i\left(PF_i^{(r)} \cdot T_i^{(r)}\right)}{\sum_i T_i^{(r)}} \tag{20}$$

$$TF^{(r)} = f^{(r)}\left(T^{(r)}\right) \tag{21}$$

$$T^{(r)} = \sum_i T_i^{(r)} \tag{22}$$

It's now possible to calculate the EAWS load score for each r-category:

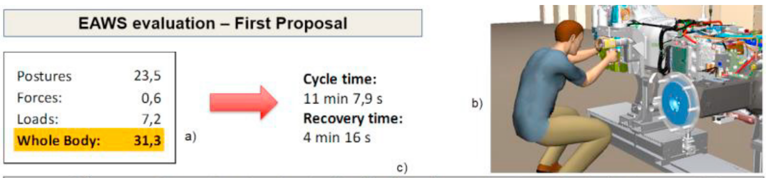
$$MHS_r = \left(LF_i^{(r)} + PF^{(r)}\right)TF^{(r)} \qquad for\ r = 1 \tag{23}$$

$$MHS_r = \left(LF_i^{(r)} + PF^{(r)} + 1\right)TF^{(r)} \qquad for\ r = 2, 3, 4 \tag{24}$$

Finally, the Manual Handling Score (MHS) is calculated by summing the scores of all the categories.

5. The industrial case study

In order to verify the validity of the proposed procedure, an industrial case study has been developed in collaboration with a global manufacturer of agriculture and industrial vehicles. The selected use case is focused on the manual assembly of cabin supports on the chassis of a tractor. The mounting task is quite complex and can be divided into 24 sub-tasks. Every task can be split up in more specific sub-tasks, according to the MTM-UAS classification. The calculation of the EAWS score for the aforementioned sequence of tasks and corresponding postures is reported in Figure 4a. The EAWS value calculated for the whole body suggests cycle or layout redesign to avoid critical tasks.



c)

Task	Type	T [s]	α1 [°]	α2 [°]	α3 [°]	β1 [°]	β2 [°]	β3 [°]	γdx [°]	γsx [°]	Legs	Force [N]	RF	Load [kg]	RM	Tool
2.1 Walk	Movement	1,8	0	0	6	0	0	5	19	14	1	-	-	-	-	
2.2 Reach screwdriver and so	Movement	4,5	16	1	1	-9	2	0	6	6	1	-	-	-	-	
2.3 Place socket	Movement	2,0	0	1	1	-9	2	0	29	30	1	-	-	-	-	
2.4 Get screwdriver	Movement	4,0	0	0	0	0	0	0	15	15	1	-	-	-	-	
2.5 Bend	Movement	4,0	22	0	1	14	0	0	15	34	4	-	-	-	-	
2.6 Place screwdriver	Movement	3,6	19	0	1	14	0	0	50	67	4	-	-	-	-	
2.7 Screw (x4)	Static	17,3	19	0	1	14	0	0	50	67	5	-	-	-	-	Electr screwdriver 487Nm

Figure 4: EAWS score for the original design (task no.2)

For example, task no. 2 (screw front support on left side) is considered and redesigned. Figure 4b shows a sub-task (2.7) of task no.2 by virtual simulation, Figure 4c contains the EAWS score for the original design for task no.2 in its sub-tasks. As shown, some sub-tasks point out critical values of angles β1, ydx, ysx and legs posture. Layout and postures can be modified in order to improve the ergonomic assessment. A new EAWS overall score can be calculated after these corrections (Figure 5). The redesign of the working cycle can bring significant benefits in terms of comfort. Similarly, the entire working cycle has been improved and validated

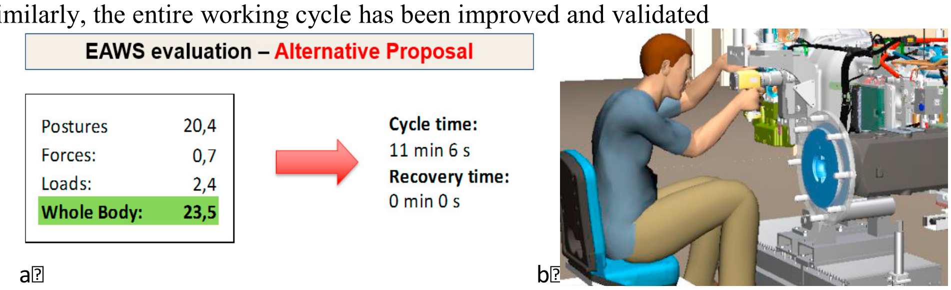


Figure 5: EAWS score for the alternative design (sub-task no.2.7)

6. Conclusions

The paper proposed a structured procedure, implemented by a dedicated Excel-VBA worksheet, to support the early evaluation of factory working cycles from an ergonomic point of view, providing a quick first-level screening tool. The integration between the EAWS method and the human modelling software Siemens Jack allowed to automatically compile an evaluation checklist and to provide a synthetic report. Different working cycles can be quickly compared, providing a quantitative ergonomic preventive evaluation of the process during the design stage, before product and factory process validation.

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