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Automatic assessment of the ergonomic risk for manual manufacturing and assembly activities through optical motion capture technology

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Abstract

Safeguard the operator health is nowadays a hot topic for most of the companies whose production process relies on manual manufacturing and assembly activities. European legislations, national regulations and international standards force the companies to assess the risk of musculoskeletal disorders of operators while they are performing manual tasks. Furthermore, international corporates typically require their partners to adopt and implement particular indices and procedures to assess the ergonomic risks specific of their industrial sector. The expertise and time required by the ergonomic assessment activity compels the companies to huge financial, human and technological investments. An original Motion Analysis System (MAS) is developed to facilitate the evaluation of most of the ergonomic indices traditionally adopted by manufacturing firms. The MAS exploits a network of marker-less depth cameras to track and record the operator movements and postures during the performed tasks. The big volume of data provided by this motion capture technology is employed by the MAS to automatically and quantitatively assesses the risk of musculoskeletal disorders over the entire task duration and for each body part. The developed hardware/software architecture is tested and validated with a real industrial case study of a car manufacturer which adopts the European Assembly Worksheet (EAWS) to assess the ergonomic risk of its assembly line operators. The results suggest how the MAS is a powerful architecture compared to other motion capture solutions. Indeed, this technology accurately assesses the operator movements and his joint absolute position in the assembly station 3D layout. Finally, the MAS automatically and quantitatively fill out the different EAWS sections, traditionally evaluated through time- and resource-consuming activities.

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Keywords: Motion capture; depth camera; markerless; assembly; manufacturing; EAWS; ergonomic; muscoloskeletal disorder; automotive.

1. Introduction and literature review

In the 21^{st} century manual manufacturing and assembly operations still represent a significant portion in production processes [1]. Indeed, most of the soft skills, specific competences and acquired experience are difficult to be taught to automated robots [2,3]. However, this framework is threatened by the alarming worsening of the operator health conditions in the last decades. 34% of the European worker experience on daily basis tiring or even painful postures performing their regular tasks, of which almost half are distinguished by short and repetitive movements that typically result in critical chronic musculoskeletal diseases. This inappropriate working conditions determined more than 150'000 occupational disease cases around Europe every year, of which about 90'000 have been certified as musculoskeletal disorders [4]. This trend is even more alarming considering that the European workforce is significantly aged. Indeed, the operator older than 50 years rose in the last 10 years from 21.6% to 30.4% of the entire European workforce.

1.1 Ergonomic assessment

This alarming scenario which depicts the actual health condition of European workers requires a specific and tailored set of normatives and standards to minimize the risk of musculoskeletal disorders during manual manufacturing and assembly activities. Two are the most relevant and widespread norms which tackle this problem, namely the international standard ISO 11228 and the European one EN 1005. In particular, the different sections of these norms focus on the analysis of different manual handling activities relevant to establish ergonomic recommendations and ensure the operator health (Figure 1). The first section of ISO

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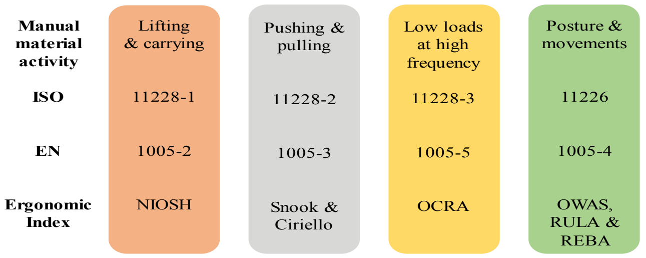
11228 (ISO 11228-1) and the second section of EN 1005 (EN 1005 -2) aim to define specific limits for repetitive and non-repetitive manual lifting and carrying of objects of 3 kg or more of weight considering several aspects of the performed task as its intensity, frequency and duration. ISO 11228-2 and EN 1005-3 focus their attention on the pushing and pulling of objects analysing its impact on the entire musculoskeletal architecture to identify potential hazards in relation to the object weight and the tools used. Furthermore, ISO 11228-3 and EN 1005-5 evaluate the tasks distinguished by handling low loads at high frequency. Finally, ISO 11226, which is the extension of ISO 11228, and EN 1005-4 are the guidelines adopted to assess the working postures hold by a worker during a manufacturing or an assembly activity.

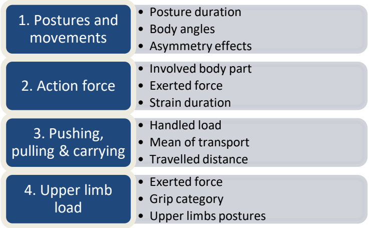
Several researchers developed in the last decades useful methods and approaches to assess the ergonomics of working conditions. These methods aim to analyse a specific manual material activity and to provide a representative index to quantitatively measure the possible risk of musculoskeletal disorders determined by the execution of certain tasks [5]. Considering lifting and carrying, NIOSH equations are adopted to define the suggested load weight limit to be lifted by human operators considering the worker sex, the forces exerted on the spine structure and the calories consumed during the effort. Pushing and pulling activities are carefully assessed by Snook and Ciriello through a detailed procedure which evaluate the exerted force to perform these activities considering the handled object weight, the frequency and duration of the action as well as the distance of pushing and pulling theirself. The handling of low loads at high frequency is tackled by Occhipinti through the OCRA index to assess the ergonomics of the upper arms while performing fast and repetitive movements handling object distinguished by a negligible weight. The postures and movements of the operator are carefully assed by a bunch of indices. Indeed, OWAS, RULA and REBA have been developed to assess the postures of the entire body both considering the upper and lower limbs as well as the spine, neck and head. These indices are of major help to provide an indication concerning the ergonomics of the entire body posture. The following Figure 1 presents the relation between the manual material activity, the ISO and EN standards as well the presented ergonomic indices.



Manual material activity	Lifting & carrying	Pushing & pulling	Low loads at high frequency	Posture & movements
ISO	11228-1	11228-2	11228-3	11226
EN	1005-2	1005-3	1005-5	1005-4
Ergonomic Index	NIOSH	Snook & Ciriello	OCRA	OWAS, RULA & REBA

Figure 1. Manual material activities assessed through the ISO and EN standards as well as ergonomic indices.

Despite these indices have been widely adopted both by practitioners and researchers, they lack in providing a unique and overall measure of the ergonomic risk. Indeed, every index focuses on a specific manual material activity. However, none of the indices previously presented consider the overall ergonomics determined by the different manual material activities. Traditionally, an operator performs several activity types during a shift or a cycle time. The Ergonomic Assessment WorkSheet (EAWS) method [6] has been developed to provide a unique ergonomic index considering the different manual material task that an operator performs [7,8]. The EAWS is made of four different sections. Each of these focuses on one of the four manual material activity previously presented. A great strength of this approach is the comparability of the results of each section. This enables to adequately identify the corrective actions with the highest positive impact on the overall operator ergonomics. The EAWS first section deals with the postures and movements of trunk and arms and it considers the posture duration, the value of the most relevant body angles and possible asymmetry effects. The second section deals with the action forces and it carefully consider the body part which exerts this force, its relative position, the exerted force and the strain duration. The third section is about the pushing, pulling and carrying activities and it considers the handled load, the mean of transport, the travelled distance and the posture held by the operator. Finally, the fourth section focuses on the upper limb load in repetitive tasks and it assess the ergonomic risk considering the exerted force, the grip category, and the upper limbs postures. The following Figure 2 summarizes the EAWS sections along with their most relevant features.



1. Postures and movements	• Posture duration • Body angles • Asymmetry effects
2. Action force	• Involved body part • Exerted force • Strain duration
3. Pushing, pulling & carrying	• Handled load • Mean of transport • Travelled distance
4. Upper limb load	• Exerted force • Grip category • Upper limbs postures

Figure 2. EAWS sections and their most relevant features.

1.2 Motion Capture technologies

In the last 15 years several researchers focused their efforts in the development of novel technologies to ease the measurement of the ergonomic risk of an operator while he is performing manual manufacturing or assembly operations. Motion capture (MOCAP) technologies represent a remarkable opportunity to monitor the operator moving in his working environment. This solution aims at the digitalization of the operator movements and postures along with the geometrical representation of the different body parts in the productive environment. Three are the major technologies adopted for MOCAP purpose.

Inertial MOCAP exploits proper sensors displaced on the human body which measure their acceleration, rotation and magnetic field on three orthogonal axes. These data are processed to offer a proper representation of the human movements and postures [9]. However, this technology does not guarantee an accurate absolute position of the limbs due to a positional drift which compounds over the recording time. Thus, this technology is distinguished by a major drawback which limits its adoption in real industrial environment.

Marker-based optical MOCAP overcome this disadvantage exploiting active or passive markers displaced in specific parts of the human body. The interpolation of the position of each marker monitored by a network of camera is adopted to provide the absolute positon of each marker in a 3D environment, measured for each monitored instant [10]. Both inertial and marker-based optical MOCAP are affected by a major limitation for their adoption in the industrial environment. The monitored operator necessarily has to wear cumbersome and uncomfortable suit where the IMUs and markers are mounted.

This major disadvantage is overcame by the latest advance in the MOCAP technologies, namely marker-less optical MOCAP. This technology frees the operator to perform his movements and activities in whatever outfit without wearing any suit nor having sensors displaced on the body [11]. Marker-less MOCAP is based on depth camera technologies to provide the 3D digitalization of the operator body. The images resulting from the depth camera are properly processed by computer vision algorithms aimed at distinguishing the human body movements from the background scene. The following Figure 3 provide an exemplification of the different MOCAP technologies presented so far.

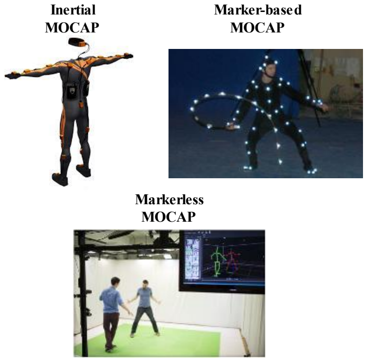


Figure 3. Exemplification of the existing MOCAP technologies.

1.3 Research contributions

Several researchers exploited the aforementioned MOCAP technologies to assess the ergonomic risk of performing manual manufacturing or assembly activities. Jayaram et al. [12] first adopted inertial MOCAP to evaluate the RULA index for an operator performing tasks in a manufacturing shop floor. Puthenveetil and Daphalapurkar [11] follow this research direction replacing the inertial MOCAP with active marker-based optical MOCAP technology. Concerning the ergonomic perspective, different authors adopted MOCAP technologies to ease the evaluation of ergonomic indices. Vignais et al. [13] assess the RULA index analysing the different body part of an human operator through the inertial MOCAP. A remarkable improvement in the ergonomic assessment is represented by the adoption of markerless optical MOCAP. Both Geiselhart et al. [14] and Plantard et al. [15] integrate multiple depth cameras to increase the accuracy and the covered area of the monitored human motions with promising results. However, as far as these authors knowledge, none research contribution focused on the EAWS assessment through MOCAP technologies. The implementation of an automatic procedure to evaluate the EAWS sections directly exploiting the data provided by a MOCAP technology it would be of great help to both minimize the resources and time required to evaluate this ergonomic index and maximize its accuracy.

Considering the analysed framework, this paper proposes an original Motion Analysis System (MAS) to automatically and quantitatively perform an ergonomic assessment of the manufacturing and assembly activities performed by human operators. The MAS is a hardware-software architecture. The hardware is made of a depth camera network aimed at markerless optical MOCAP whereas the software aims the digitalization of the operator movements and postures in relation to the workstation layout. This features enable the MAS to calculates a huge set of ergonomic indices, as the different EAWS sections (Section 2). The MAS is tested and validated with an industrial case study of a European automotive manufacturer in real working environment (Section 3). The results suggest how this architecture is able to provide reliable data and to accurately evaluate the desired ergonomic index in a limited amount of time (Section 4).

2. Motion Analysis System

MAS is an original hardware-software architecture developed for the ergonomic analysis of manufacturing and assembly systems in which the operations performed by human operator are of major importance. MAS is able to adapt itself to different workplace configurations and its purpose is the automatic and quantitative analysis of the human work content providing the production management with a very detailed report from the ergonomic perspective. This goal can be obtained thanks to a markerless MOCAP hardware developed for the digitalization of the operator body and an original software customized to calculate a bunch of relevant ergonomic indices performed through a dynamic analysis. Finally, the user has to provide the MAS a set of input date to enable the architecture to automatically analyse the operations performed by the operator. These input are in the following:

- Physical features of the operator, height in particular;
- 3D workplace layout including position and geometrical dimensions of machines, racks, shelves, workbenches, etc.;
- Information of the product to be assembled or manufactured (bill of materials, dimension and weight);
- Information of the product components and tools (dimensions and weight);
- Tools and product components position within the workstation;
- Relation between component and tool used for the product manufacturing or assembly.

2.1 Hardware architecture

The hardware structure of MAS relies on a Wi-Fi network with up to four depth cameras each connected each to a server PC. The camera network exploits one PC as a master and the remaining as the slaves. This configuration is necessary to manage the synchronism between the different images get by the cameras and from multiple point of views and obtain a final and unique representation of the monitored operators. The desired synchronism is obtained through a custom calibration procedure. A light-bulb emitter is simultaneously shown to each camera while it is performing circular paths at different heights in the environment to monitor. The developed procedure suggests different diameters and trajectories considering the shape, dimensions and occlusions of the monitored area.

The developed MAS architecture adopts Microsoft Kinect v.2 as depth cameras. The technical features of the adopted depth cameras are summarized in the following:

- Time of flight technology.
- RGB sensor resolution of 1080p at 30 Hz.
- Depth sensor resolution of 512x424 at 30 Hz.
- Minimum/maximum tracking distance: 1.5/6.0 m.
- Horizontal/vertical field of view: 70°/60°.
- Tracked human body: 26 body joints simultaneously
- Contemporarily acquirable operators: 2.

Concerning the system configuration, the camera position must be carefully chosen to maximise the acquisition precision and the covered monitored workstation area. Ideal camera configuration presented in Figure 4 guarantees the best precision of the human skeleton acquisition. Indeed, the absolute positional error between the digital and the real tracked body part position is about 4-5 cm. Furthermore, each camera is provided with a tailored Neutral Density (ND) filter mounted on the RGB and depths sensors. This ND filter is necessary to enlarge the light contrast range of the camera device and it must be chosen from ND=0.3 to ND=3.8 in relation to the intensity of the bright surfaces (windows, lights, reflective metal surfaces, etc.) within the area to analyse. Without the ND filter, the system performance dramatically decreases.

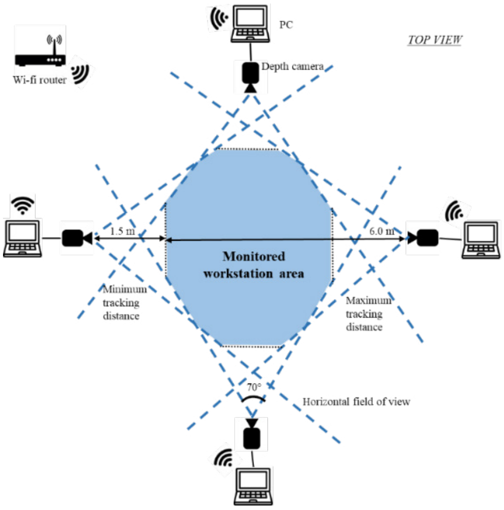


Figure 4. Ideal configuration of the MAS hardware architecture.

2.1 Software architecture

A customized software has been developed to provide a dynamic analysis of the ergonomic risk which threats the monitored operator during his manufacturing or assembly tasks. This analysis exploits the human body digitalization offered by the depth camera network previously presented (Figure 5).

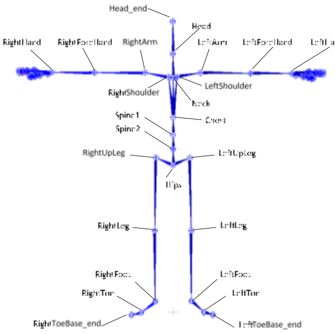


Figure 5. Skeleton joints of the acquired human body

A maximum of two operators can be monitored simultaneously. The digitalization of their bodies consists in the recording of their skeleton movements by the different cameras, e.g. without providing a real-time digitalization and representation of the operators. A software has been adopted to off-line analyse the stream of depth images obtained by the synchronised cameras. A properly trained artificial neural network is exploited to calculate for each monitored frame the most likely position of each body joint. The artificial neural network compares the acquired depth images to the ones used in the training phase to identify the human body shape. The body joint positions are further refined to ensure a constant length of the body limbs over the entire recording period and plausible human postures.

The aforementioned software is able to provide as output a file which dynamically stores all the body joint positions over time. The absolute position of these joints in the 3D production environment for each tracked frame obtained through the depth camera network is summarized in Table 1. The position vectors (X, Y, Z) of each joint is listed and stored frame by frame providing a dynamic representation of all the movements executed by the operator.

Table 1.Body joint positions over time recorded in the output file.

Frame [#]	Time [sec]	Body Joint 1: Hips			Body Joint 2: Spine			Body Joint 3…
		X [cm]	Y [cm]	Z [cm]	X [cm]	Y [cm]	Z [cm]	X [cm]
456	45.07	13.96	927.96	24.12	52.83	1031.56	29.12	…
457	45.10	13.86	927.20	23.75	52.70	1030.80	28.95	…
458	45.13	13.93	926.45	23.44	52.77	1030.04	28.77	…
459	45.17	14.00	926.20	23.37	52.85	1029.78	28.67	…

All this information is adopted by the MAS to determine the angle of every human body articulation for each monitored frame, thus all the movements and postures of the operator are automatically and quantitatively measured by the software architecture.

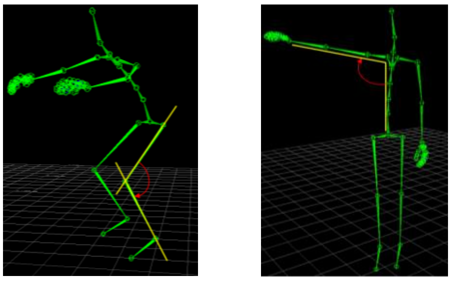


Figure 6. Examples of angles assessed by the MAS.

All the angles which are automatically evaluated in the 3D workstation environment and the joint position vectors enable to evaluate a set of relevant ergonomic KPIs. The information about the operator ergonomic performance provided by the MAS deals with the evaluation over time of several indexes as:

- Articulation angle analysis applying the ISO 11226 standard to classify as acceptable or not the worker postures;
- OWAS for body posture analysis;
- REBA and RULA for body postures analysis;
- NIOSH, for weight lifting activities;
- The first 3 sections of EAWS for entire body analysis and specific of the automotive sector.

Between the aforementioned indices, the automatic and quantitative assessment of EAWS represents a distinctive feature of the MAS software architecture. Indeed, this index is widely adopted in several industries, as the automotive one, in which the most relevant companies consider it a required standard for a holistic measurement of the worker ergonomic conditions. However, the traditional process required to calculate all the different sections of the EAWS is time and resource consuming. Indeed, the ergonomic specialists typically film the operators while they are performing the production tasks and sequentially watch these movies to manually analyse the performed operations and fill out the different EAWS sections. The MAS architecture is able to automatically and quantitatively fill out the first 3 sections of such an ergonomic index, e.g. it is not possible to assess section 4 “Upper limb load in repetitive tasks”. In particular, the MAS exploits the following available data for each section (Figure 7).

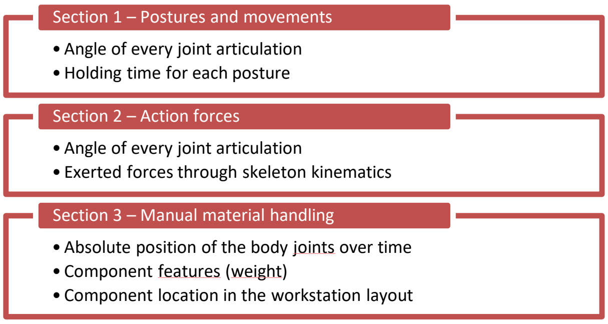


Figure 7. Available data from the MAS for the automatic and quantitative assessment of the EAWS sections.

The characteristics of the industry in which the MAS is adopted to assess the EAWS index is of major importance to make the MAS self-sufficient for the EAWS whole body score. Indeed, this latter score is determined by the following Eq. 1 in which the section 4 score is typically the greatest component for highly repetitive workshift, e.g. cycle time of few minutes.

$$EAWS_{whole\ body} = max[(EAWS_1 + EAWS_2 + EAWS_3); EAWS_4] \quad \text{Eq. (1)}$$

Thus, the MAS is able to provide all the relevant information needed to assess the EAWS whole body score for those industries distinguished by a sufficiently wide work content, as the automotive sector, or the assembly systems with a cycle time greater than a couple of minutes.

3.Case study and results

To test and validate the presented hardware-software architecture, the MAS is adopted to analyse the ergonomic risk of an operator performing assembly operations in an automotive two sided assembly line of a European manufacturer. The analysis focuses on the left side of an assembly workstation distinguished by a cycle time of 16.6 minutes, a 20 sqm area and three trolleys containing the tools and the components to be mounted on the vehicle (Figure 8). Their weight, dimensions and 3D positions are known and acquired. A quasi-rectangle displacement of the depth camera is adopted to capture the operator movements which can dress any type of clothes without colour restriction.

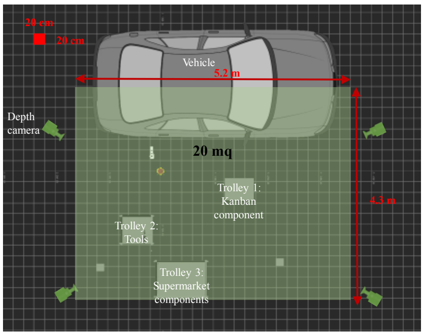


Figure 8. Assembly station layout.

Within this context the MAS is adopted to automatically and quantitatively assess the ergonomic risk of the operator through a proper index. Considering the automotive industry, the EAWS evaluation is of major concern. Thus, the MAS is exploited to assess the first 3 sections of this index, the most relevant one considering the cycle time of the monitored assembly line. The EAWS whole body score is 67.0 which represents a high risk for the operator health and it requires an immediate corrective action. Consequently, the MAS is exploited to further detail the most critical EAWS section, namely postures and movements one. Considering the section 1 constituents, the posture score is the worst determining 12.7 of the 37.0 score of this section. Furthermore, the bent forward position is responsible for 7.2 of these points (Figure 9).

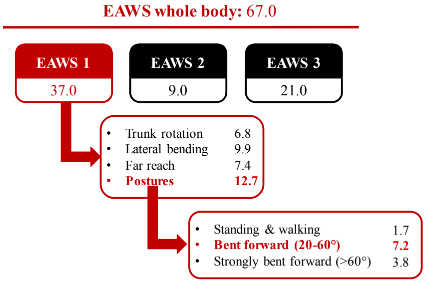


Figure 9. EAWS breakdown analysis.

A customized analysis provided by the MAS suggests how this ergonomic risk is determined by the great portion of the cycle time spent by the operator to perform assembly task at the wheel and suspension level as well for the picking tasks near to the ground (Figure 10). This powerful automatic analysis immediately suggests the analysts to develop corrective measures to improve this ergonomic aspects, e.g. provide to the operator a swivel stool to limit his trunk bending.

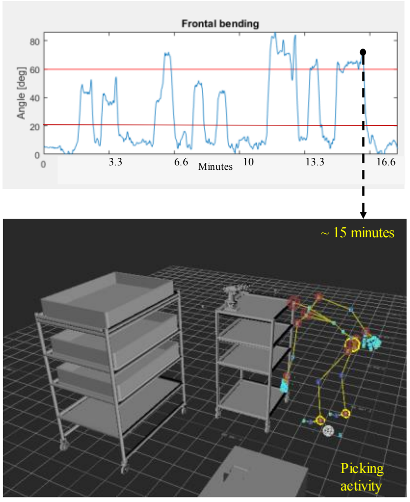


Figure 10. Example of MAS posture assessment to analyse the trunk forward bent over the cycle time.

4.Conclusions

This paper presents an original hardware-software architecture, called Motion Analysis System (MAS) to automatically and quantitatively analyse the ergonomic risk of an operator which performs manual manufacturing and assembly activities in an industrial environment. The hardware architecture is made of a depth camera network which are adopted to accurately digitalize the operator movements and postures in the production environment. Indeed, this technology frees the worker to perform his activities in his regular outfit without wearing any cumbersome suit. Furthermore, the adopted depth camera can be exploited for any workplace environment since their precision is not affected by the traditional equipment. The software architecture exploits the data provided by the depth camera to automatically and quantitatively measure all the body joint angles and to monitor over time the interaction of the operator with the workstation layout, e.g. track the initial and final instant of a lifting operation along with the handled object features (weight). This information is exploited by the MAS to calculate a set of ergonomic indices, as the NIOSH, OWAS, RULA, REBA and the first 3 sections of the EAWS. For this latter in particular, the MAS represents a remarkable aid to save resources and time typically needed by the analysts to fill out all the EAWS sections.

The MAS is tested and validated through a case study of a European automotive manufacturer in a two-sided assembly line. The MAS is adequately set up to monitor the activities of an operator in the workstation layout, his postures, movement and interaction with the car, components and tools. The case study results proposed the detailed assessment of the first 3 sections of the EAWS index. A top-down analysis is performed to identify which actions determined a high risk of musculoskeletal disorders for the operator. In particular, the trunk frontal bending determined a remarkable portion of the high score assigned at the aforementioned ergonomic index. This precious information automatically determined by the MAS enable the analysts to promptly focus on adequate and specific corrective actions to ensure the operator health.

Further research activities should integrate the information provided by MAS with a manufacturing optimization tool able to rearrange the location of tools and product components within the workstation to improve both the ergonomic performance of the operator. In this context, the MAS will be used to automatically evaluate the industrial workplace before and after the optimization measuring the achieved improvement.

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