Motion analysis system for the ergonomic assessment of manufacturing and assembly manual activities

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Abstract: The environment of manufacturing and assembly manual activities radically evolved in the last decades. First, the western world workforce is alarmingly aging. In the last 15 years the percentage of European employees older than 50 years rose from 21.6% to 30.4%. Furthermore, the latest developments in legislations (EU Machinery directive, 2006/42/EC, 89/391/EEC, Occupational Safety and Health act) force the companies to assess, monitor and safeguard the health of their operators. Finally, an increasing pressure from the civil society and the stakeholders pretends safe working conditions in manufacturing and assembly processes. This paper tackles these issues proposing an original Motion Analysis System (MAS) for the ergonomic assessment of human operators involved in industrial processes. This research exploits different motion capture (MOCAP) technologies, e.g. optical, inertial and miscellaneous, to register the static postures and the dynamic movements of an operator during manufacturing or assembly activities. The information provided by the MOCAP technologies about the evolution over time of the position and orientation of the skeleton segments are processed by the MAS. This system calculates for each monitored frame the angle values of all the relevant joints of the human body accurately reproducing the operator movements. Furthermore, the MAS assesses the risk of musculoskeletal disorders of the performed manufacturing and assembly activities with the automatic evaluation of three ergonomic indices considering the features of the products and tools which the operator pick and handle. Along with the calculation of REBA and OWAS indices, an original one is developed and proposed based on the ISO 11226:2000 norm. The MAS is tested and validated with the industrial case study of a gearbox assembly process comparing the novel ergonomic index with the traditional ones. The results suggest that the proposed index accurately evaluates the ergonomic risk of specific assembly tasks compared to the classical approaches.

Keywords: Ergonomic, Motion capture, Assembly, Manufacturing, Body posture.

1. Introduction and literature review

Manual manufacturing and assembly operations represent a remarkable portion of nowadays industrial activities (Faccio et al., 2015). The competences, flexibility and experience which distinguish human operators to automated robots is still a competitive advantage for most of 21st century companies (Bortolini et al., 2016). However, the industrial environment is dramatically evolved in the last decades. First, the workforce is alarmingly aging. In the last 15 years the percentage of European employees older than 50 years rose from 21.6% to 30.4% (OECD, 2015). 5.9 million people of today European workforce are older than 60 years (7.4% of the total workforce). Furthermore, one third of all workers in the European Union are involved in painful or tiring postures for more than half of their working day, and close to 50 % of all workers are exposed to short repetitive tasks, which are mostly accompanied by painful and tiring movements (Paoli and Merllie, 2001). These inappropriate and hazardous working conditions determined the dramatic amount of 155'639 cases of occupational diseases across Europe in 2014 only, of which 91'684 have been recognized as musculoskeletal disorders. Furthermore, this statistic is alarmingly worsened in the last decade with an increment of 42% from 2007 to 2014 (Kieffer, 2016).

To face this urgent challenge, a wide regulatory and normative framework has been developed to ensure appropriate and safe working conditions to human operator. A well-known and widely adopted set of norms and standards aim to minimize the risk of musculoskeletal disorders of operators during manufacturing and assembly activities as the most frequent disorders in occupational health. The three parts of ISO 11228 establish ergonomic recommendations for different manual handling tasks. Aim of this norm is the specification of recommended limits for material manual handling, defining the mass of objects in combination with working postures, frequency and duration of manual handling which operators are expected to exert when carrying out manual handling activities. The first part of ISO 11228 defines specific limits for both repetitive and non-repetitive manual lifting and carrying of objects of 3 kg or more of weight considering the intensity, the frequency and the duration of the task. The second section of ISO 11228 provides quantitative methods to identify potential hazards and risks associated with whole-body pushing and pulling of objects. The latter part of ISO 11228 norm is focused on low load handling at high frequency. The evaluation of working postures, required by the norm 11228, is typically performed adopting the guidelines proposed by ISO 11226. Indeed, this norm provides relevant information to assess static working postures. Each body part is carefully analysed to define the angles and the holding time which distinguish an acceptable from a not recommended working posture.

At European level, the standard 1005 deals with the safety of machinery and the human physical performance. EN 1005-1 provides the terms and definitions on concepts and parameters used by the following standard parts. EN 1005-2 deals with the manual handling of machinery and component parts of machinery and objects processed by the machine of 3 kg or more. This standard provides relevant information for the ergonomic design and risk assessment concerning lifting, lowering and carrying in relation to the assembly, operation, maintenance and disposal of machineries. EN 1005-3 specifies recommended force limits for several actions performed by the operator during machinery operation. EN 1005-4 proposes guidelines which deal with the movements and posture of operators performing tasks in relation with machineries. Finally, EN 1005-5 presents guidance in assessing and controlling health and safety risks due to machine-related repetitive handling at high frequency specifying reference data for action frequency of the upper limbs.

Finally, the European normative framework for working condition assessment, ergonomic analysis and musculoskeletal disorders evaluation includes the European standard EN 547. EN 547 – part 1 describes the principles for determining the dimensions required for openings for whole body access into machiner. EN 547-2 specifies the dimensions of openings for access to machinery whereas EN 547-3 provides all the relevant information to properly measure the human body aimed at the application of standards EN 547-1, -2 and beyond. The following Table 1 proposes the framework of the analysed international and European standards aimed at the assessment and of risk of musculoskeletal disorders for human operator.

Table 1. International and European standards for the assessment of manual handling activities.

Manual handling activity	ISO standard	EN standard
Lifting & carrying	11228-1	1005-2
Pushing, pulling and force limit	11228-2	1005-3
Low loads at high frequency	11228-3	1005-5
Posture & movements	11226	1005-4
Body measurement	-	547-3

During the last decades, several methods and approaches are proposed by the literature to assess the ergonomics of working conditions and to evaluate the risk of musculoskeletal disorders (Li and Buckle, 2017). Considering the analysed normative and standard framework, the ergonomic indices are classified in the following with respect to the targeted manual material handling activity.

Lifting and carrying tasks are traditionally assessed through the NIOSH equation. This method determines the recommended load weight limit for human lifting operations considering biomechanical, physiological and psychophysical aspects. The first deals with the maximum compression force on the L5/S1 vertebral segment of spine, the second aspect assesses the maximum energy expenditure during lifting operation whereas the latter considers the maximum acceptable lifted weight for male and female workers. Both ISO 11228-1 and EN 1005-2 standards are based on the NIOSH equation.

Pushing and pulling activities along with force limit considerations are assessed by Snook and Ciriello. The authors estimate the force limits for pushing and pulling activities for male and female operators considering the task frequency and duration along with the pushing distance and height as well as the handled object size.

The manual handling of low loads at high frequency is carefully analysed by Occhipinti. The proposed index assesses the exposure to repetitive movements of the upper limbs for manual activities. The developed OCRA index lowers the number of tasks which can be performed by an operator during a shift considering the force exerted and the duration of each repetitive task. Furthermore, the shoulder, elbow and wrist movements are carefully assessed to properly evaluate the ergonomic risk of these tasks. Then OCRA index is exploited by both ISO 11228-3 and EN 1005:5 for the development of their guidelines and recommendations.

Similarly to OCRA, the Strain Index estimates the risk of distal upper extremity disorders analysing different features of a performed task, namely intensity, duration and speed of exertion as well as the number of exertion per minute, the wrist movement and the duration per shift.

Finally, the operator postures and movements are carefully assessed by three indices. Both OWAS, RULA and REBA analyse the working posture of an operator evaluating the position of the different body parts and the angle of several skeleton joints. However, the OWAS index approximatively estimates the body posture. RULA carefully assesses the upper limbs (wrists included) but it poorly estimates the posture of lower limbs, the legs in particular. Finally, REBA index is distinguished by the advantages of RULA along with a proper and thorough evaluation of lower limbs posture. Unfortunately, all the indices for operator postures and movements approximatively considers the lifted weight without any relation to the adopted body posture. The following Table 2 summarizes the features of the presented indices for the ergonomic assessment of manual material handling activities.

Table 2. Distinctive features of the indices adopted for the ergonomic assessment of manual material handling activities.

Feature	NIOSH	Snook & Ciriello	OCRA	Strain Index	OWAS	RULA	REBA
Posture			X	X	X	X	X
Upper limbs			X	X		X	X
Lower limbs					X	X	X
Spine	X				X	X	X
Quantitative	X	X	X	X		X	X
Load/Force	X	X		X		X	X
Frequency	X	X	X	X			
Duration		X	X	X			
Recovery			X				

Recent technology advances significantly ease the assessment of musculoskeletal disorder risk during manual manufacturing and assembly activities. The most relevant solution is the motion capture (MOCAP. This technology enables to accurately record the activities of the human body proposing a virtual representation of the skeleton and its movements. Three different technologies have been developed to ease the tracking of human movements.

Marker-based optical MOCAP exploits active or passive markers properly displaced in specific part of human body. A bunch of cameras detects the position of each marker in its own two-dimensional (2D) field of view, whereas the relative position and orientation of cameras enable to triangulate the location of markers in the 3D space of action. The markers can be either active or passive. Active markers are LEDs which emits light at high frequency. On the contrary, passive markers are small plastic spheres coated with a retroreflective material to reflect the light that is generated near to the cameras lens by an infrared emitter (Tian and Duffy, 2011). The absence power supply for markers is the greatest advantage of this latter MOCAP configuration. However, optical MOCAP does not offer a real-time representation of the skeleton movements since it requires a time- and resource-consuming pipeline to postprocess the captured data.

Inertial MOCAP technology is based on miniaturized inertial sensors which are properly displaced on the body parts to monitor. Each inertial measurement unit (IMU) is equipped with a gyroscope, a magnetometer and an accelerometer to record their relative measures on each of the three geometrical axis (Bourkea et al., 2008). The biomechanical model implemented on a proper software offers in a real time fashion the position and rotation of each monitored body part. However, compared to optical MOCAP, the inertial approach is affected by a lower accuracy of the absolute location of the limbs due to positional drift which can compound over the recording time.

Marker-less optical MOCAP represents a recent advance in the technology to avoid the awkward suits worn by the human operator in case of marker-based optical or inertial MOCAP. Indeed, both these technologies typically mount the active and passive markers as well the IMUs on cumbersome suits. On the contrary, marker-less optical MOCAP frees the human actor to perform his activities in his regular outfit. This MOCAP system is based on two different camera technologies. Structured light cameras project a band of light on a 3D shaped surface to produce a line of illumination used for the exact geometric reconstruction of the surface shape since the reflected light is not distorted uniquely from the projector perspective. On the contrary, time-of-flight camera emits infrared signals on 3D surfaces and measure the reflected signal through a depth sensor. The comparison between the speed of light and the time of flight to receive back the signals enables to determine the 3D position of each pixel recorded by the camera for each monitored frame (Zanuttigh et al., 2016). The following Figure 1 classifies the analysed MOCAP technologies based on their most relevant features, namely data processing, wearable devices and measurement accuracy.

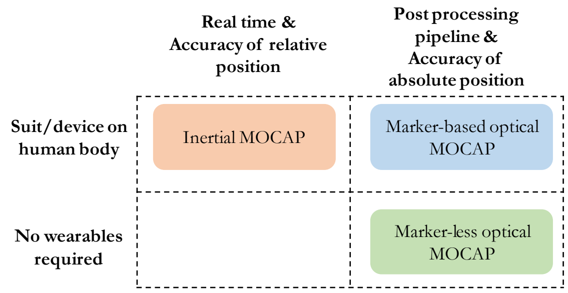

Figure 1. MOCAP technology classification based on data processing, wearable devices and measurement accuracy.

In the last years, several research contributions focused on the adoption of different MOCAP technologies for the ergonomic assessment of manual manufacturing and assembly activities. The pioneering contribution of Jayaram et al. (2006) exploits inertial MOCAP to automatically assess the RULA index for the different postures assumed by the operators during their working activities. Puthenveetil and Daphalapurkar (2015) follow this research direction replacing the inertial MOCAP with active marker-based optical MOCAP technology. From the ergonomic analysis perspective, two contributions aim at improving the ergonomic evaluation. Vignais et al. (2013) assess for each body part the risk of musculoskeletal disorders adopting an inertial MOCAP technology along with the RULA ergonomic index. Kim and Nussbaum (2013) further detail the ergonomic evaluation monitoring the evolution over time of most of the skeleton joints angles. Furthermore, some authors recently exploited the emerging marker-less optical MOCAP technology for industrial application. Both Geiselhart et al. (2016) and Plantard et al. (2016) integrate multiple depth cameras to increase the accuracy and the covered area of the monitored human motions with promising results. Finally, the integration of inertial and marker-less optical MOCAP in a so-called fusion MOCAP technology, represents a promising research direction to simultaneously overcome the disadvantages of these technologies and benefit of all their strengths (Atrsaei et al., 2016).

Considered the analysed framework of standards, indices and technologies for the ergonomic assessment of manual industrial activities, this paper proposes an original Motion Analysis System (MAS). This system exploits different

MOCAP technologies, e.g. marker-less optical, inertial and fusion, to monitor the static postures and the dynamic movements of an operator during manufacturing and assembly activities. For each monitored frame, the MAS calculates the angle values of all the relevant joints of the human body accurately reproducing the operator movements (Section 2). Furthermore, the MAS assesses the risk of musculoskeletal disorders of the performed activities with the automatic evaluation of three ergonomic indices. Along with the calculation of REBA and OWAS indices, an original one is developed and proposed based on the ISO 11226 and EN 1005-4 standards to properly assess the impact of the lifted weights considering the adopted body postures (Section 3). Finally, the MAS is tested and validated with the industrial case study of a gearbox assembly process comparing the novel ergonomic index with the traditional ones (Section 4).

2.Motion Assessment System

The developed MAS integrates three different MOCAP technologies. A network of time-of-flight depth cameras is settled to obtain a MOCAP area wide enough to be compatible with the most common manufacturing and assembly activities. The technical features of the adopted depth camera are a color camera resolution of 1080p at 30 Hz, a depth sensor resolution of 512x424 at 30 Hz and a maximum field of view of 5.0 meters. The integration of multiple camera enables to increase the monitored area, reduce the joint tracking occlusion and increase the MOCAP precision. The second MOCAP technology adopted is a suit of 32 IMUs distinguished by a dynamic range of 360 degree, an accelerometer range of ±16 g, a gyroscope range of ±2000 dps and a resolution of 0.02 degree. The IMUs are properly integrated into a suit to offer the position and orientation of the body joints in which the IMUs are displaced at 60 Hz with a latency of about 15 ms exploiting a customized biomechanical model for the skeleton representation. Finally, the two aforementioned technologies are properly integrated into a fusion MOCAP system. This latter system relies on the data acquired from both the MOCAP technologies and merge them to obtain the most accurate representation of the body postures and movements. Indeed, the optical MOCAP system offers reliable information about the absolute position of the joints in the working area, whereas it is affected by tracking occlusion. On the contrary, inertial MOCAP accurately assesses the relative position of the joints, it does not present any occlusion problem but it is affected by joint positional drift over recording time.

The fusion MOCAP system offers at 30 frame per second (fps) the position and orientation of 65 body joints connected by specific bones. The MOCAP joints represent the articulation of the human body whereas the MOCAP bones represent the human limbs. The physical connection between joints and bones is defined by the skeleton hierarchy and it is of major importance to associate a skeleton articulation to each joint. As shown by Figure 2, 22 are the main joints which univocally define the operator posture, 3 are the effector joints which delimitate the joint hierarchy at feet and head level and 15 are the joints of each hand, one per phalanx. Furthermore, an original filter is developed to correct the joint position over time due to possible measurement errors of the MOCAP technologies. The filter analyses the evolution of the joint position and corrects their trajectory to make it feasible with realistic acceleration and deceleration profiles, different for each body part.

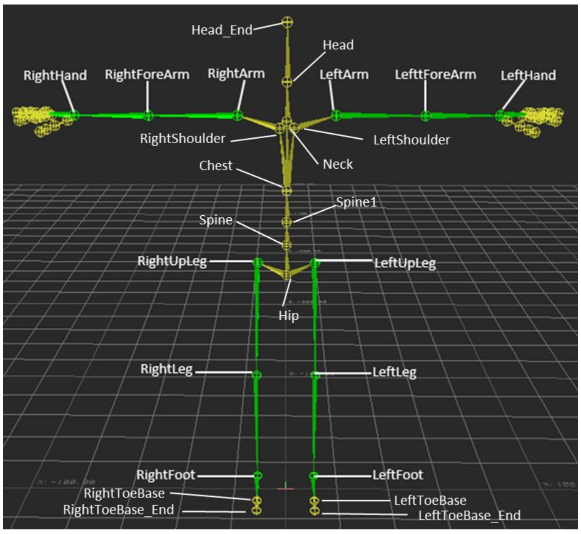

Figure 2. Body joints of the developed MOCAP system.

The big volume of data provided by the developed MOCAP system is represented by the absolute geometric coordinates of each joint in the working space. Thus, the MOCAP system offers for each of the 30 fps recorded 195 geometrical values which univocally represent the skeleton posture. All this information enable to determine the angle of every human body articulation for each monitored frame, thus their movement over time. The angle of the wrists, elbows and knees (e.g. cylindrical joints) have been determined exploiting the 3D Carnot theorem to a proper triplet of joints for each articulation (Figure 3.a). On the contrary, the trunk is distinguished by three possible inclinations, namely frontal bending, lateral bending and rotation. These angle estimation requires to define the sagittal, frontal, transverse and lower limb planes exploiting certain joints. In particular, RightArm, LeftArm and Spine joints univocally define the frontal plane, Spine2, Neck and the midpoint between Right- and LeftShoulder identify the sagittal plane, the transverse plane corresponds to the floor, whereas RightUpLeg, LeftUpLeg and their midpoint projection on the floor define the lower limb plane. Exploiting these definitions, the trunk frontal bending is the angle between the frontal and transverse planes, the trunk lateral bending is the angle between the sagittal and transverse planes whereas the trunk rotation is measured with the angle between the frontal and lower limb planes (Figure 3.b). Finally, the spherical joints of the shoulders and neck are distinguished by solid angles in the 3D space. Thus, the movement of these human body parts is modelled through the definition of two 2D angles for each solid angle. Namely, the projection of the RightForeArm, RightArm and RightUpLeg joints on sagittal plane defines the shoulder frontal bending angle (Figure 3.c) whereas their projection on the frontal plane defines the shoulder lateral bending angle. Finally, the projection of the Neck, Head and Head_End joints on sagittal plane defines the neck frontal bending angle whereas their projection on the frontal plane defines the neck rotation angle.

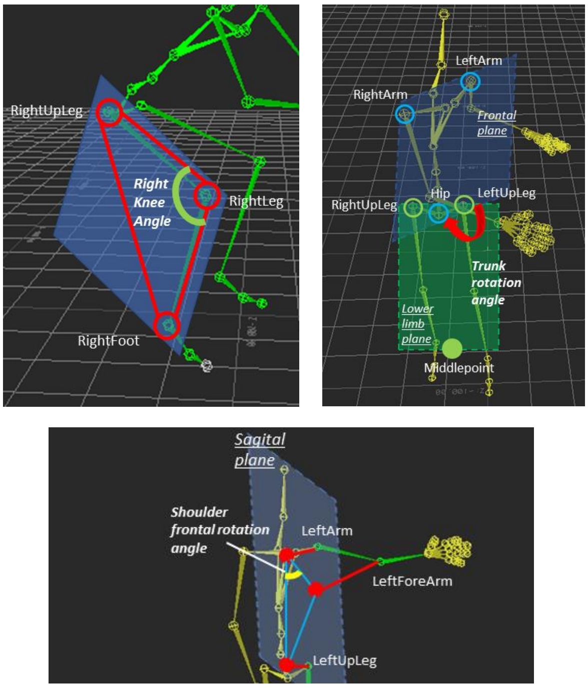

Figure 3. Body articulation angles: knee (a), trunk rotation (b) and shoulder frontal bending (c).

3.Ergonomic indices evaluation

The presented MAS offers an accurate value of the angles of all the relevant skeleton joints for each monitored frame of the assembly or manufacturing activity. This big volume of data can be exploited for the dynamic and automated assessment of the ergonomic indices which evaluate the postures and movements of operators during working activities. This research implements the OWAS and REBA evaluation into the developed MAS. For a proper calculation of these indices, the MAS considers for each frame the weight of the handled object by the operator hands. Each hand is independently assessed to monitor the handling activity performed by the operator. Along with the joint angles, the lifted weights enable the exact evaluation of the operator postures and movements through OWAS and REBA indices. However, as presented in Section 1, these indices are distinguished by two severe limitations. First, both the indices do not adopt linear methods to merge the risk level of the different body parts into the final ergonomic index. This obstructs any possible analysis on the relative impact of each body part posture on the final risk level. Furthermore, the lifting activities are poorly assessed since the handled object weight is approximatively considered to increase the global value of these indices. Thus, a novel and original assembly and manufacturing ergonomic index (AMEI) is developed and proposed in this research to overcome both the limitations of the traditional ergonomic indices. AMEI independently assesses the posture of 6 body parts, namely the neck, truck and legs, as well as the left and right shoulders, forearms and wrists. Aim of this index is the definition of the risk level for each body part. The risk level is arbitrarily divided in 5 classes as presented in the following Table 5. The score associated with each body part posture is accurately assessed evaluating the relevant joint angles for the analyzed body part. The angle values which distinguish a safe, a potentially dangerous or a hazardous posture are the one suggested by ISO 11226, ISO 11228-3, EN 1005-4 and EN 1005-5 standards. Furthermore, incremental scores identify awkward postures (Table 3).

Table 3. Angle ranges of the considered body joints for AMEI evaluation.

BODY PART	INDICATOR	POSTURE							
Neck		**Frontal bending**				**Rotation**			
	Angle [deg]	-20°÷0°	0°÷10°	10°÷20°	>20°	>45°			
	AMEI Score	3	1	2	4	+2			
Trunk		**Frontal bending**				**Lateral bending**		**Rotation**	
	Angle [deg]	0°	0°÷20°	20°÷60°	>60°	15°÷30°	>30°	15°÷30°	>30°
	AMEI Score	1	2	3	5	+1	+2	+1	+2
Knee		**Bending (standing)**			**Bending (sitting)**				
	Angle [deg]	0°÷30°	30°÷60°	>60°	< 90°	90°÷135°	>135°		
	AMEI Score	1	2	4	2	1	2		
Shoulder		**Frontal bending**					**Lateral bending**		
	Angle [deg]	< -20°	-20°÷20°	20°÷45°	45°÷90°	> 90°	>45°		
	AMEI Score	3	1	2	4	5	+1		
Elbow		**Bending**							
	Angle [deg]	0°	60°÷100°	0°÷60°	> 100°				
	AMEI Score	1	3	2	4				
Wrist		**Bending**							
	Angle [deg]	0°	-15°÷15°	< -15° OR > 15°					
	AMEI Score	1	2	4					

Each body part is independently evaluated to assess the associated risk level determined by a certain posture. Furthermore, the sum of neck, trunk and knee AMEI scores defines α, the ergonomic index of spine and lower limbs, whereas the sum of shoulder, elbow and wrist scores determine β_l and β_r, the ergonomic indices of upper left and right limbs, respectively. The risk level associated with α, β_l, β_r scores is presented in Table 5. According to ISO 11228-1 standard, the AMEI accurately assesses the impact of the lifted weights on the risk of musculoskeletal disorders for the trunk and spine. In particular, L5-S1 vertebral segment is typically stressed by remarkable compression forces during manual loading activities. In contrast to the common belief, this force is not maximum for a complete truck bending (90°) but the partial bending (20÷60) is the most hazardous movement (Chaffin and Page, 1994). Thus, the final AMEI score is increased by WI considering both the lifted weight and the trunk posture as proposed by the following Eq. 1 and Table 4 both derived from the NIOSH lifting equations (Waters et al., 1993). According to EN 1005-2 standard, the lifted weight range is between 3 and 20 kg. A lower weight determines a negligible risk of musculoskeletal disorder whereas current European regulations limit the maximum lifetable weight by workers to 20 kg for safety reasons.

$$WI = a \cdot lifted\ weght - b \qquad \text{(Eq. 1)}$$

Table 4. AMEI increment due to weight lifting and trunk posture.

Trunk frontal bending angle	a value	b value
0° ÷ 20°	0.176	0.517
20° ÷ 60°	0.471	1.41
> 60°	0.35	1.02

The AMEI final score is determined considering the body side (e.g. left or right) according to Eqs. 2-4 whereas Table

5 proposes the respective risk level of musculoskeletal disorders.

$$AMEI_l = \alpha + \beta_l + WI \qquad \text{(Eq. 2)}$$

$$AMEI_r = \alpha + \beta_r + WI \qquad \text{(Eq. 3)}$$

$$AMEI_{final} = max(AMEI_l; AMEI_r) \qquad \text{(Eq. 4)}$$

Table 5. Risk classes of the developed AMEI ergonomic index.

Risk level	Body part score	α, βL,βr scores	AMEI final score	Suggested action
Null	1	-	-	-
Negligible	2	3 ÷ 4	6 ÷ 8	No action required
Low	3	5 ÷ 7	9 ÷ 14	Possible corrective action
Medium	4	8 ÷ 10	15 ÷ 20	Required corrective action
High	≥ 5	≥ 11	≥ 21	Immediate corrective action

4.Industrial case study of manual assembly activities

The MAS is exploited to assess the ergonomic postures of an operator during the assembly process of a gearbox in an industrial assembly station. The worker is 178 cm tall and weights 76 kg. 27 components whose weight ranges from 10 g to 13.2 kg are assembled to obtain a gearbox. The 4.3 m per 2.7 m shop-floor area is tracked with the fusion MOCAP system presented in Section 2 made of a set of time-of-flight depth cameras integrated with customized IMUs. Figure 4 presents the dynamic trunk angle evaluation proposed by the MAS. In particular, this information suggests to focus on frames 425 and 525 of the assembly process. Indeed, these frames are respectively distinguished by a trunk frontal bending of 85°, a trunk rotation of 44° (frame 425) and a trunk lateral bending of 23° (frame 525). Frame 425 depicts the risk of musculoskeletal diseases due to component picking from a shelf almost at floor level, whereas frame 525 represents the awkward posture to screw a component into the gearbox. The MAS dynamically evaluates and graphically represents the value of all the skeleton joints to facilitate the identification of the most critical postures during the assembly process.

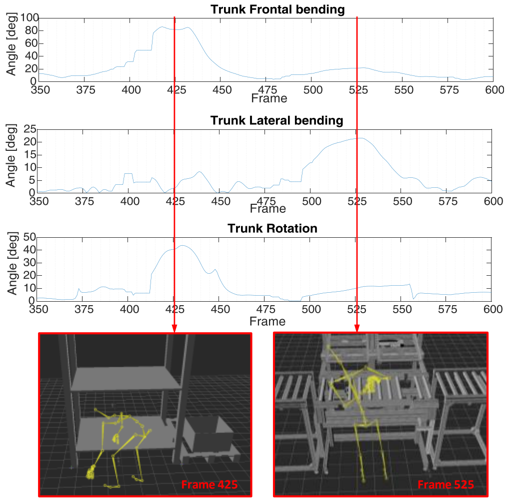

Figure 4. Dynamic evaluation of the trunk angles and related hazardous body postures.

Furthermore, the MAS is adopted to assess the working postures through the dynamic and automatic evaluation of the proposed three ergonomic indices during the entire assembly process. As shown in Figure 5, the OWAS index considers all the operator postures from frame 1700 to 2400 of class 2, with no ergonomic risk variation during the monitored period. The REBA index slightly improves this performance evaluating the operator movements with no or low risk of musculoskeletal disorders. Only the AMEI properly assesses the operator postures during the assembly process. Differently from the previous indices, even a limited variation in the worker posture determines a change in the index score (e.g. frames from 2050 to 2100). This accuracy of the ergonomic assessment avoids any underestimation of musculoskeletal disorder risk for every analysed movement. For instance, the postures from frame 2023 to 2283 are considered of medium risk by the AMEI only, whereas both the OWAS and the REBA indices classify them as low risky, e.g. not hazardous.

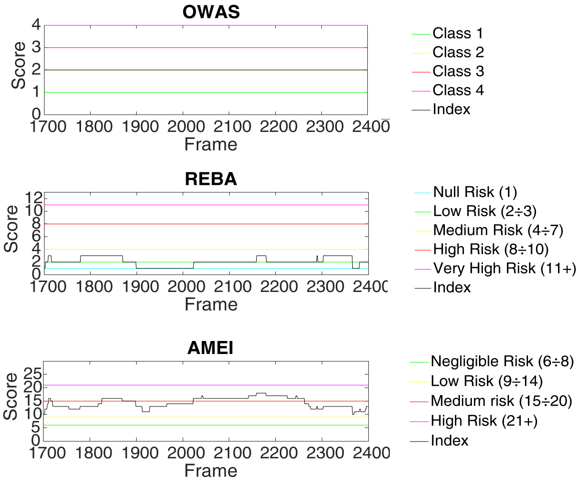

Figure 5. OWAS, REBA and AMEI comparison for the assessment of manual assembly process (frame 1700- 2400).

Finally, the MAS enables to decompose the AMEI as well as the other indices to assess the risk of musculoskeletal disorders for each body part and tracked frame. Figure 6 proposes this analysis for the posture of frame 525 already depicted in Figure 5 presenting the operator during the assembly of light components (less than 3 kg) to the gearbox unit on the workbench. The standing posture of the operator minimizes to 1 the AMEI score for his knees, whereas the limited lateral bending of the worker trunk results in an AMEI score of 3 for this body part. The neck frontal bending of 13° and its rotation of 47° require corrective actions to lower possible injuries to this body part. Furthermore, of major interest is the comparison between the right and left upper limbs. Right limbs are much more stressed compared to the left ones. In particular, the right shoulder is distinguished by a high risk of musculoskeletal disorders due to a frontal and lateral bending both greater than 45°. The AMEI score of 5 for this articulation requires immediate corrective actions. These risk levels of the different body parts result in a final AMEI score of 17 which classifies this posture with a medium risk of musculoskeletal disorders and it suggests corrective actions, to the right shoulder and neck, in particular.

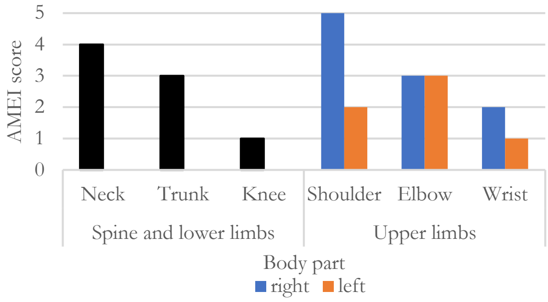

Figure 5. Ergonomic assessment of the operator posture in frame 525 through the AMEI.

5.Conclusions and further research

This paper proposes an original Motion Analysis System (MAS) for the automatic and dynamic assessment of the ergonomic risk of manual assembly and manufacturing activities. The MAS adopts a fusion MOCAP technology to track the human operator movements and postures, namely a set of time-of-flight depth cameras integrated with customized IMU sensors. For each monitored frame, the MAS calculates the angle values of all the relevant joints of the human body accurately reproducing the operator movements. Furthermore, the MAS assesses the risk of musculoskeletal disorders of the performed activities with the automatic evaluation of three ergonomic indices. Along with the calculation of REBA and OWAS indices, an original one is developed and proposed based on the ISO 11226 and EN 1005-4 standards to properly assess the impact of the lifted weights considering the adopted body postures. The MAS is tested and validated with the industrial case study of a gearbox assembly process comparing the novel ergonomic index with the traditional ones. The case study results suggest how the new index outperforms both the traditional ones since even a limited variation in the worker posture determines a change in the score of the novel index, only. This ergonomic assessment accuracy avoids any underestimation of musculoskeletal disorder risk for each movement analyzed. Finally, the novel index assesses this risk for each body part and tracked frame. This feature enables to analyse each posture to identify the most critical operator limbs from the ergonomic perspective. Thus, specific corrective actions can be planned to reduce the musculoskeletal disorder risk of the identified limbs and consequently to reduce the ergonomic risk of the entire body posture.

Further research should test and integrate further MOCAP technologies in the MAS, as marker-based optical systems and structured light depth cameras. Moreover, the MAS should be tested and validated in industrial environments different to assembly stations, as storage and retrieval systems and manufacturing departments.

References

Atrsaei, A., Salarieh, H., and Alasty, A. (2016). Human Arm Motion Tracking by Orientation-Based Fusion of Inertial Sensors and Kinect Using Unscented Kalman Filter, *Journal of Biomechanical Engineering, 138*(9), 1–13.

Bortolini, M., Faccio, M., Gamberi, M., and Pilati, F. (2016). Including Material Exposure and Part Attributes in the Manual Assembly Line Balancing Problem. *IFAC-PapersOnLine*, *49*(12), 926–931.

Bourke, A. K., Donovan, K. J. O., and Olaighin, G. (2008). The identification of vertical velocity profiles using an inertial sensor to investigate pre-impact detection of falls, *Medical Engineering & Physics 30 (7)*, 937–946.

Chaffin, D. B. and Page, G. B. (1994). Postural effects on biomechanical and psychophysical weight-lifting limits. *Ergonomics, 37(4)*, 663-676.

Faccio, M., Gamberi, M., Pilati, F., and Bortolini, M. (2015). Packaging strategy definition for sales kits within an assembly system. *International Journal of Production Research*, *53*(11), 3288-3305.

Geiselhart, F., Otto, M., and Rukzio, E. (2016). On the use of Multi-Depth-Camera based Motion Tracking Systems in Production Planning Environments. *Procedia CIRP*, *41*, 759–764.

Jayaram, U., Jayaram, S., Shaikh, I., Kim, Y., and Palmer, C. (2006). Introducing quantitative analysis methods into virtual environments for real-time and continuous ergonomic evaluations, *Computers in industry, 57(3)*, 283–296.

Kieffer, C. (2016) *Musculoskeletal disorders: What recognition as occupational diseases? A study on 10 European countries*. EUROGIP, Paris. ISBN- 979-10-91290-79-1.

Kim, S., and Nussbaum, M. A. (2013). Performance evaluation of a wearable inertial motion capture system for capturing physical exposures during manual material handling tasks. *Ergonomics*, *56*(2), 314–326.

Li, G., and Buckle, P. (2017). Current techniques for assessing physical exposure to work-related musculoskeletal risks , with emphasis on posture-based methods, . *Ergonomics, 42(5)*, 674-695.

OECD (2015). *OECD Employment Outlook 2015*, OECD Publishing, Paris.

Paoli, P. and Merllié, D. (2001). *Third European survey on working conditions 2000.* Office for Official Publications of the European Communities, Luxembourg. ISBN 92-897-0130-7.

Plantard, P., Shum, H. P. H., Pierres, A. Le, and Multon, F. (2016). Validation of an ergonomic assessment method using Kinect data in real workplace conditions. *Applied Ergonomics*, IN PRESS. DOI: 10.1016/j.apergo.2016.10.015.

Puthenveetil, S. C., and Daphalapurkar, C. P. (2015). Computer-automated ergonomic analysis based on motion capture and assembly simulation. *Virtual Reality*, *19*(2), 119-128.

Tian, R., and Duffy, V. G. (2011). Computers & Industrial Engineering Computerized task risk assessment using digital human modeling based Job Risk Classification Model. *Computers & Industrial Engineering*, *61*(4), 1044–1052

Vignais, N., Miezal, M., Bleser, G., Mura, K., Gorecky, D., and Marin, F. (2013). Innovative system for real-time ergonomic feedback in industrial manufacturing. *Applied Ergonomics*, *44*(4), 566–574.

Zanuttigh, P., Marin, G., Dal Mutto, C., Dominio, F., Minto, L., and Cortelazzo, G. M. (2016). *Time-of-Flight and Structured Light Depth Cameras*. Springer. ISBN 978-3-319-30971-2.