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New easy to use postural assessment method through visual management

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ABSTRACT

Earlier studies have demonstrated the strong relationships between manual assembly work with a high repetition level and the presence of repetitive strain injuries (RSI) or repetitive motion illnesses (RMI). Moreover, recent works have also correlated the high physical load level in assembly lines with an increased number of quality defects in finished products. Thus, the ergo-quality level of a manual workstation needs to be carefully monitored not only to respond to the legislation but first of all to ensure a high system productivity level in the medium-term perspective. The objective of this study was to develop and test a new easy-to-use postural assessment tool and its performance in a car component assembly system. The results show the promising potential of the methodology particularly when compared with the well-known OCRA method.

1. Introduction and problem definition

This research was motivated by the observation of manual operations in a real automotive assembly system characterized by simple manufacturing cycles and fast tasks and aims to define a general ergonomic methodology which could be applied to similar industrial realities. After an analysis of manual assembly tasks in car component manufacturing, results showed several significant correlations between ergonomics and operation complexity, recovery time and assembly task failures.

In order to increase the assembly system efficiency and quality, a high ergo-quality level is required in all workstations since high physical load levels and high complexity levels are not acceptable. Benefits provided by ergonomics application in assembly systems design are first of all linked to the reduction in occupational injury risks, and to the improvement of physical and psychosocial conditions of the workforce, with a drastic reduction in all costs linked to absence, medical insurance and rehabilitation (Carey and Gallwey, 2002).

Despite the many different approaches offered in literature for analyzing the ergo-level of a working task, managers need new easy-to-use postural analysis protocol able to support posture analysis by means of visual intuitive maps and speed up the process evaluation (Battini et al., 2011 and Battini et al., 2014). In addition, several activities performed in assembly systems, in particular those associated with repetitive movements and with considerable level of stress or with extended assumption of uncomfortable postures, might be correlated to the insurgence of Work Related Musculoskeletal Disorders – WMSD (Cecchini et al., 2010). For this reason, it is becoming of paramount importance to create a research that develops and validate an integrated approach in assembly system design, and takes into account technological variables (related to assembly times and methods) and environmental/ergonomics variables (i.e. human diversity). However, in several cases, ergonomics evaluations happen too late in the design process, hence, only minor ‘ergonomic’ adaptations and corrections can be made and ergonomics is perceived as a time-consuming and costly activity (Dul and Neumann, 2009). Proactive risk identification in early product development stages is still unusual although today much scientific evidence is available to confirm both the human and economic benefits of a proper ergonomic fit. Corrective assembly ergonomics measures are often made late, and reactively, only when problems have already occurred (Falck and Rosenqvist, 2014). The consideration and implementation of ergonomic practices can generally be regarded as a means to preserve and enhance a company's workforce and therewith its competitiveness above all

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for automotive manufacturers, where workers are required to fulfill physical and strenuous tasks on the shop floor (Thun et al., 2011).

Considering this assumption, this research focuses on developing and testing a new easy-to-use postural analysis tool for a full body ergonomic assessment which is capable of:

- considering additional factors related to action repetitiveness, steps walked and loads handled, which are sometimes excluded by other ergonomic methods.
- evaluating the full body rather than only body portions
- applying a visual management approach offered by a new set of visual ergonomic assessment maps, in order to speed up the analysis and reduce the analyst training time.

The approach presented is achieved by condensing the most recognized method for full body (Rapid Entire Body Assessment – REBA, Ovako working posture analysis system – OWAS) and upper limb (Rapid Upper Limb Assessment – RULA and OCRA checklist) ergonomic assessment and by adding peculiarities related to overload and repetitiveness as in the OCRA checklist and OWAS. The main goal of such methodology is to offer a wider vision of overall exposure to ergonomic risk and to provide clear suggestions for corrective actions to reduce ergonomic risk.

The basic research goals addressed by the present work may be outlined as follows: (i) To design a methodology for a full body ergonomic assessment taking into account both postures and physical efforts by considering (1) repetitiveness of operations and (2) load handled during the working shift; (ii) To provide a fast analysis method for the identification of possible risks to posture requiring a further deepened analysis and corrective actions. The second goal is here achieved by developing a document tool (made up of a set of visual ergonomic assessment maps) easily accessible according to the visual management approach paradigms.

2. Literature review

The problem of unfavorable working conditions, or poor workplace ergonomics, is a hot topic today. Ergonomic risks at the workplace cause a lot of damage to the health and quality of life of workers, and are financially damaging for employers and the economy as a whole (Otto and Scholl, 2011).

In the past, ergonomics was always aimed at designing tools and working environments which were comfortable and suitable for human use. Nowadays the objectives of ergonomics can be identified as the usability and safety of systems where the operator is considered as a user and an integral part (Vignais et al., 2013). Ergonomics can therefore be configured as the study and design of complex systems whose effectiveness is determined by the functioning of the system and its sustainability in terms of technological, economic and social features. Attention is paid to the interaction between human and machine within the production cycle. The task is performed by involving all production phases in order to improve health, safety, welfare and operator satisfaction, and, at the same time, reduce rising costs of ergonomic nature. In particular, Guimarães et al. (2012) studied correlations between ergonomic improvement, increased sales and expense reduction by performing a cost-benefit analysis on a test line of a manufacturing plant. Similarly, investigations and discussions on the interconnections between ergonomics and productivity and management can be found in several authors (Kihlberg et al., 2002; Dul et al., 2004; Dul and Neumann, 2009; Battini et al., 2011).

Referring to productivity in most industries, work-related musculoskeletal disorders or WMSDs have been recognized as a health issue leading to considerable loss of productivity among workers with highly physical jobs. Meanwhile, posture, repetition and duration have been identified as the main risk factors of WMSDs in highly repetitive tasks instances (including assembly tasks) (Cheshmehgaz et al., 2012). WMSDs imply additional high costs related to absent workforce, medical insurance and rehabilitation, which cause significant expenditures not only to the company but also to the public in those countries with a public health system. In this context, synergies between the design of assembly systems and ergonomic features must be adopted to guarantee a reduction in global costs owed to injuries. Kee et al. (2011) studied laws governing WMSD prevention in Korea and introduced corrective actions designed to ensure ergonomic improvement in a big automotive context by evaluating impacts and positive reflections regarding production processes. In particular, they paid attention to the analysis of repetitive movements and uncomfortable postures during assembly phases. Extensive reviews or researches on the issue, including assembly or automotive lines can be found in literature (Ouellet and Vezina, 2014; Ferguson et al., 2011) with reference to shoulder disorders (van Rijn et al., 2010), carpal tunnel syndrome (van Rijn et al., 2009), dynamic spinal stability (Graham et al., 2012), low-back disorder in parts distribution (Lavender et al., 2006) but also to age management aspects (Landau et al., 2008).

2.1. Research on ergonomic exposure in manufacturing and assembly lines

There is substantial epidemiologic evidence of associations between physical ergonomics exposure at the workplace, such as lifting, constrained postures, repetitive movements, fast work pace, heavy material handling, forceful exertions and vibration, and the occurrence of upper extremity musculoskeletal disorders (d'Errico et al., 2007), associated with the fact that assembly workers are involved in jobs characterized by prolonged standing, which decrease the blood flow to the muscles, accelerate the onset of fatigue, and cause pain in the leg, back and neck muscles. Excessive standing may also cause the joints in the spine, hips, knees and feet to become stiff or locked (Balasubramanian et al., 2009). Bao et al. (1996) followed optimization and rationalization processes of a big production firm dealing with ergonomics of production processes. Their aim was to evaluate the ergonomic impact of workloads before the planned improvements and to compare them with the future state of the line. Similarly, Gooyers and Stevenson (2011) showed the existing link between working cycle time and ergonomic load of an operator during manufacturing operations; twelve operators participated in the simulation of a working session to test a new semi-automatic tool. Mirka et al. (2001) presented a research project for the development and evaluation of technical control to reduce low back injury risks in workers in the furniture manufacturing industry; an analysis of injury/illness records and survey data identified upholsterers and workers in the machine room as at elevated risk of low back injury. Neumann and Medbo (2010) presented a design stage comparison of an existing "big box" material supply strategy common in Swedish manufacturing with a proposed "narrow bin" (NB) approach common in Japanese production systems which is used to make logistics activities more efficient. Biomechanical loading on the spine and shoulder for a given workstation were analyzed with reference to these two opposite approaches. They demonstrated that the NB approach is preferable in terms of both productivity and ergonomics since it improves loads on the vertebral column.

Automotive production systems (e.g. assembly or disassembly) are oftentimes characterized by a large number of various processes in highly automated environments, which can have severe consequences for the number and nature of tasks performed by employees. In this context are simple, monotonous, and highly repetitive tasks leading to one-sided strains and consequent diseases of the muscular-skeleton system are potentially harmful (Thun et al., 2011). At the same time, the manual lifting and handling of heavy loads is usually accompanied by unnatural and uncomfortable body postures which have to be rectified. Kazmierczak et al. (2005) focused their attention on a Swedish car disassembly firm in order to design a database for musculo-skeletal disorder data. They aimed to evaluate actual exposure to ergonomic risks for defining optimization processes and prevent diseases and injuries. The study showed that disassembling implied pronounced circulatory loads, and more walking and higher lumbar peak loads were found than in studies of assembly work. In addition, value added activities (VAAs) constitute 30% of the overall operations and imply painful postures for head, arm and wrist. This study suggested indications to improve working conditions by introducing mechanization to reduce ergonomic risks and increase the number of VAAs.

Ferguson et al. (2011) quantified exposure to musculo-skeletal disturbance in a car assembly plant by evaluating loads and postures assumed by operators during their shift; vertebral column and shoulder loads were evaluated by dividing the car cabin into eight regions. Ten operators were analyzed through the use of (1) ECG for the evaluation of upper limbs and (2) goniometers for trunk angles. Then data were compared with the effect of a cantilever chair introduced to alleviate certain postures. Such inexpensive intervention has reduced postural stress and improved productivity in some cases.

As stated by Thun et al. (2011) in their analysis in the automotive industry in Germany, the most negative impacts and ergonomic risk factors that were identified are: time pressure (67%), one-sided monotonous exposures (64%), and hard physical labor (41%). Jobs which require high degrees of stretching and bending should be avoided altogether, while empirical research reveals that manual materials handling or highly repetitive activities are particularly harmful (Xiao et al., 2004). Enomoto et al. (2012) discussed a scoring method of ergonomics parameters of an assembly operation, including visibility, reachability, eye sight direction and glance. Cort et al. (2006) examined the problem of manual fastener initiation in assembly line to reduce the insurgence of wrist injuries to workers on the production line. Reviewed literature takles the automotive sitting posture problem which affects ankles, knees, hips, shoulders, elbows, wrists and neck. Battini et al. (2011) developed a methodological framework which takes into account technological variables related to work times and methods by combining back, legs, arms, and head with technological and environmental variables (e.g. human diversity), while Graham et al. (2012) assessed work-related low back disorders related to spinal stability in automotive assembly lines.

2.2. Research and insights on comparison of ergonomic methods

Beside the previous scientific approaches, several research works have compared different ergonomic evaluation methods of workloads, highlighting their strengths and weaknesses. It is worth mentioning that the number of methods adopted for ergonomic evaluation is large, but no single one is exhaustive. Different approaches are needed for different goals and the selection of the appropriate tool can be challenging (Takala et al., 2010). Some popular examples of assessment methods (Andreoni et al., 2009) are (1) RULA, (2) OCRA checklist, (3) REBA and (4) OWAS.

The RULA algorithm is commonly used to evaluate the exposure of workers to the risk of upper limb disorders (Öztürk and Esin, 2011). It assesses the risk based on posture, muscle use, weight of loads, task duration, and frequency, and determines if the task carries the risk of an upper limb injury through the uses of a series of illustrations of different body postures. This analysis evaluates a posture and rates it on a scale from one to seven, one being most comfortable, and proposing an overall numerical score. In accordance to the review of Takala et al. (2010), the inter-observer repeatability has been found to be acceptable, although the methodological information on the repeatability studies is so scant that its quality cannot be evaluated.

Similarly, the OCRA checklist is a procedure for the identification and estimation of ergonomic risk to upper limbs; it is very useful in the earliest stages of an ergonomic assessment to evaluate the risk exposure of the workforce. Such methods have wide applicability in mechanical, food, wood and ceramic industrial sectors as well as laundries, salons and post offices (Cecchini et al., 2010). Four main risk factors are taken into account: lack of rest intervals, frequency, strength and incorrect postures. Such factors are combined with temperature, vibrations, precision works and so on to estimate exposure to ergonomic risks (Colombini et al., 2002), while no studies on the repeatability of the method were indicated by Takala et al. (2010).

In contrast, REBA has been designed to provide an ergonomic method involving upper limbs and lower limbs at the same time (Hignett and McAtamney, 2000). It is based on partition of the body into functional segments which have to be evaluated separately according to static and dynamic muscular activities. A final stage connects the previous evaluations providing action levels which indicate the timing for the application of corrective actions of prevention or protection. The method provides an overall score that takes all the body parts into account (trunk, legs, neck, shoulders, arms and wrists). The overall score takes into consideration the same additional factors as RULA as well as the quality of hand-coupling (Chiasson et al., 2012). Takala et al. (2010) found similarities with the OWAS method but no reports associations with MSWD, and reported that inter-observer repeatability was moderately good for leg and trunk postures but not for upper limbs.

In full body assessment methods, OWAS (Roman-Liu, 2014) analyzes postures assumed by the operators, grouping them into configurations with reference to back, arm and leg position and to lifted weights. Four risk classes are identified and an index is obtained which synthesizes the criticality level of the ergonomic state (Cimino et al., 2009). OWAS is based on direct observation and can be very time-consuming, but has shown good intra- and inter-observer repeatability (Takala et al., 2010).

Some studies present methods from the literature according to their various characteristics but few studies compare the results of the methods (Chiasson et al., 2012) and those that do are mainly qualitative (Joseph et al., 2011). Among these, in terms of quantitative exposure measures Jones and Kumar (2007) examined the agreement between five ergonomic risk assessment methods including RULA, REBA and OCRA. Spielholz et al. (2008) evaluated two subjective assessment methods for physical work-related musculoskeletal disorder risk factors from 12 companies in the manufacturing and healthcare industries. Brown and Li (2003) applied the quick exposure check (QEC) for workplace risks, assessing a number of industrial tasks simultaneously by using QEC and RULA and comparing the assessment scores from both methods whereas Russell et al. (2007) compared the results of methods of lifting assessment. Drinkaus et al. (2003) compared the ergonomic risk assessment of a task for the upper extremities as determined by RULA and the Strain Index through the analysis of 244 automotive assembly plant tasks. Chiasson et al. (2012) presented a comparison of eight methods to determine risk factors of musculo-skeletal diseases in different industrial sectors. Two hundred and twenty-four workplaces and 567 working activities have been analyzed by comparing results according to the three risk categories (low, medium and high) to provide a full picture of the particularities of the different approaches. Otto and Scholl (2011) studied different methods to control ergonomic risks within the manufacturing sector, highlighting the need for line balancing among operators Kee and Karwowski (2007) compared the OWAS, REBA and RULA methods using data from a sample of 301 postures collected in various industrial sectors. Generally speaking, Takala et al. (2010) provided an interesting review of more than 30 ergonomic assessments methods from literature, grouped them as general, upper limb and manual material handling methods, and revealed strengths, limitations and metrics of each method by classifying them as follows:

- Strengths: easy to use; selection of most items based on literature research; consideration of recovery periods; individual capacity; comprehensive of lifting, carrying, pushing and pulling; taking into account most risky factors with duration and frequency;
- Limitations: lack of metrics; does not consider duration of exposures; qualitative method; time consuming; subjective; covering a limited number of risk factors; the user has to make many decisions with vague rules;
- Metrics: yes/no answer; frequency of items or postures; sum score of weighted items; sum score of positive findings; posture discomfort score; risk index.

Such analysis is an important reference to define the characteristic of an ergonomic assessment.

3. Research methodology

The selection (in our case the design) of a method should be based on (i) its goals, (ii) the characteristics of the work to be assessed, (iii) the individual(s) who will use the method, and (iv) the resources available for collecting and analyzing data (Takala et al., 2010). This work is based on the assumption of Roman-Liu (2014), i.e. that "*a comprehensive assessment … for a variety of work tasks could be based on already available methods*" combining few methods by mixing similarities and differences. Our proposal rises from the direct observation of assembly tasks in automotive environment and the extensive literature review of section 2, which suggests the following characteristics in ergonomic assessment and design:

- a full body method: as stated by d'Errico et al. (2007) and Balasubramanian et al. (2009) (see section 2.1), an ergonomic assessment for assembly lines operators must analyze at least upper and lower limb exposure; in addition, when considering repetitive tasks for the upper limbs, the back and the lower limbs are loaded at the same time, as well (Roman-Liu, 2014).
- Additional factors external to mere limbs have to be involved: as an example, Takala et al. (2010) identified duration/frequency as one external factors and ease to use as strength points of an ergonomic assessment as another (see section 2.2);
- A fast detection method for criticalities: To the best of our knowledge, and from what emerged from the existing literature, a lack of a fast detection of ergonomic criticalities and subsequent late intervention in solving any issue needs to be remediate. The present approach tries to fill in this gap.

In this sense, the present work analyzed four assessment systems to design a new assessment methodology, i.e. RULA and the OCRA checklist for upper limb assessment and REBA and OWAS for entire body assessment. Some missing analyses from the single methods are introduced by the methodology to define an overall evaluation of ergonomic risk. In particular, 14 domains resulting from the in-depth literature analysis have been selected for typical body areas and operator actions. Such domains can be classified as follows:

(1) *Upper limb*: neck, trunk, waist, wrist (rotation and bending), arm and forearm.
(2) *Lower limb*: knee and leg.
(3) *Stereotypy, loads, typical actions*: frequency, material withdrawal, special movements, steps, loads.

The criticality evaluation was given by a score suggesting the overall gravity of the operations performed by the operator. According to predefined ranges, corrective actions can be suggested or must be introduced to reduce the overall gravity. Rating methods based on single or multiple (sub) scales are more popular among ergonomics specialists and range from relatively simple to complex (Cheshmehgaz et al., 2012). However, the peculiarity of our score relies in their evaluation: differently from other methods such as REBA, it does not require the use of tables or cascade evaluations.

As anticipated, the methodology proposes a visual management approach for the identification of intervention areas, which provides an easy way to detect critical operations. The priority of interventions to reduce ergonomic risks is accomplished ordering the operations criticalities with Pareto diagram.

Operations performed by operators are analyzed through direct observation and video recording (Shuval and Donchin, 2005) and supported by participatory ergonomics (Sundin et al., 2004). If necessary, slow replays can be used for a more precise evaluation of postures as in Bao et al. (1997). The optimum number of observations may depend on the exposure variability in relation to measurement duration and frequency, as well as on the exposure measurement strategy chosen (e.g. individual or group-based measurement strategy), but the criteria for determining the optimum number of observations for low and high repetitive tasks are still unclear (Genaidy et al., 1994). Currently, according to Burdorf (1995), no general guidelines are available to control and evaluate the trade-off between repeated and prolonged exposure measurements in a group of workers. In the present case, due to high repetitive and simple manufacturing tasks and in accordance to previous works (Jones and Kumar, 2007; Ferguson et al., 2011) a set of 10 repetitions have been observed which can be processed to obtain an average posture and an average duration value. Observational methods are probably the most commonly used approach to evaluate physical workloads, in order to identify hazards, monitor the effects of ergonomic changes, and conduct research on these issues (Takala et al., 2010). It is also worth noting that observations and direct measurements can be regarded as true standards of exposure to physical stressors only if the observation or measurement period is representative of the actual average of workers' exposure. Sometimes a long observation time may be necessary for workers in non-routine jobs who have many variable tasks, and thus need to be observed or measured for several days in order to obtain a valid assessment (d'Errico et al., 2007). However, this is not always true in automotive or assembly sector which is characterized by high repetitive tasks within short machine cycle times.

Definitely, the main steps of the research methodology can be outlined as follows:

1. The division of all the activities into "elementary operations." Such operations are those performed by an operator during his/her working shift and form the subject of the ergonomic analysis.
2. Each elementary operation is involved in the ergonomic assessment, in accordance with the ergonomic fields selected

for the present methodology. This step allows the association of a gravity color to each field according to its criticality.
3. An overall score is evaluated for summarizing the state of the operator during manufacturing operations. A partial score is associated with each color which allows us to compute the overall score.
4. Depending on the score, it may be decided to intervene to reduce the overall criticality score, i.e. improving ergonomic conditions through corrective actions towards operations characterized by higher gravity. The identification of such actions is rendered possible by the visual management approach.

The following sections explain the methodology in more detail.

3.1. Step 1 – division into "elementary operations"

In this step all elementary operations (EOi) are identified through direct observation and video recording. The core task is to analyze single operations by defining the ergonomic criticality of each of them, e.g. as in RULA or OWAS. Vice versa, some methods assign a criticality class to the operator instead of operations, as in the OCRA checklist.

For a full division of manufacturing tasks, cyclic and non-cyclic operations must be included in the analysis. Repetitive actions may cause ergonomic problems, too. In particular:

- Cyclic operations are those performed within line cycle time.
- Non-cyclic operations are those performed with a lower frequency than the previous ones.

Such elementary operations can be included in a spreadsheet and will be involved in the ergonomic assessment. A sample extracted from a real case is provided in Table 1.

3.2. Step 2 – ergonomic assessment

The proposed ergonomic assessment is applied to each elementary operation. Some main postures and operator behaviors, i.e. *ergonomic domains*, have been selected and a different color is associated with each of them, representing the ergonomic criticality. Such assignment allows us to obtain a bar diagram visually representing the overall state of a certain elementary operation.

Domains of ergonomic analysis were identified by referring to body areas and actions according to the well-known ergonomic assessment methods.

With reference to color assignment which is used to represent ergonomic criticality, three levels have been assigned to each of the identified postures, as follows: Low (Green color), Medium (Yellow color) and High (Red Color) Criticality.

Criticality is decided according to the indicator selected for the specific ergonomic domains, as shown in Table 2.

Fig. 1 shows the 14 domains selected to cover the three previously described ergonomic areas and the bounds of the respective indicators.

Table 1
Elementary operations – extract.

EO#	Operation description
1	Lee plug – withdrawal and positioning on pallet
2	Cover – withdrawal and positioning on line pallet
3	Housing – withdrawal and positioning on line pallet
4	Withdrawal and depositing in GZ of cover pallet
5	Withdrawal and depositing in GZ of housing pallet
6	Removing shelves and division of housing box
7	Lee plug – Station 20 supply

Table 2
Ergonomic domains and indicators.

Ergonomic domain	Indicator
Trunk	Bending
Waist	Rotation
Arm	Position for material withdrawal
	Height
Wrist	Rotation
	Extension/Bending
Knee	Bending
Special movement	Rotation on axis
Steps	Walked step
Handled load	Carried loads in kilos
Neck	Bending and rotation
Forearm	Rotation
Leg	Position
Frequency	Percentage with respect to working time

Cut-off values have been defined with respect to ergonomic assessments methods from the literature, adapting them on a three level criticality scale (red, yellow and green). For example, trunk bending angles derive from the adaption of the four gravity levels (0; 0–20; 20–60; >60) of RULA, while wrist bending angles are the same of RULA. Other values are described later on. The only exception is related to the values of walked steps and carried loads as they reflect the typical scenarios of the observed case study.

From the posture analysis it is possible to create a bar diagram of each ith elementary operation (EOi) which provides a visual trend of ergonomic criticality. The bar diagram reports the elementary operation on the x-axis and the number of ergonomic domains grouped by criticality class on the y-axis.

Fig. 2 provides an example of visual analysis of elementary operation ergonomics: EO_1, EO_2 and EO_3 are characterized by two postures of high criticality (red color), two of medium criticality (yellow color) and the remaining ten of low criticality (green color). These operations are more critical than EO_4, which is characterized by no postures in high criticality, three postures of medium criticality (yellow color) and eleven of low criticality (green color). In this context, color disposal allows immediate identification of critical operations, suggesting at the same time the operations requiring special attention. This indication is particularly useful at step 4, where we have to define intervention priorities for corrective actions designed to reduce overall ergonomic criticality.

In the following sections, three examples of (1) upper limb, (2) lower limb and (3) stereotypy analysis describe the ergonomic assessment in more detail.

3.2.1. Neck stress – upper limb

In accordance with RULA and REBA ergonomic assessment methods, criticality neck posture has been divided with reference to the angle created between the neck and vertebral column, as follows:

(1) Bending between zero and 20° (low criticality).
(2) Bending higher than 20° (medium criticality).
(3) Bending higher than 20° with head rotation (high criticality).

In this case, cut-off values of the level 1 and 2 correspond to those of REBA for neck flexion while level 3 is reached if also rotation is observed. Fig. 3 shows the critical levels for such upper limb assessment.

3.2.2. Leg stress – lower limb

The analysis of the OWAS ergonomic assessment method

TRUNK BENDING ANGLE			WAIST ROTATION ANGLE			ARM HEIGHT			WRIST ROTATION ANGLE		
LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3
> 30°	15° ÷ 30°	0° ÷ 15°	> 45°	15° ÷ 45°	0° ÷ 15°	Over shoulders	At shoulders	Weist height	> 180°	90° ÷ 180°	0° ÷ 90°

KNEES BENDING ANGLE			MATERIAL WITHDRAWAL POSITION			ROTATION ON AXIS ANGLE			WALKED STEPS NUMBER		
LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3
> 60°	30° ÷ 60°	0° ÷ 30°	Two hands needed	Stretching an arm	Without stretching an arm	> 90°	45° ÷ 90°	0° ÷ 45°	> 10	5 ÷ 9	0 ÷ 4

CARRIED LOADS KILOS			NECK BENDING OR ROTATION ANGLE			FOREHARM ROTATION ANGLE		
LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3
> 5	3 ÷ 5	< 3	>20° and rotation	>20°	0° ÷ 20°	>90° and crossed	>90°	0° ÷ 90°

LEG POSITION			WRIST BENDING ANGLE			TASK DURATION (F) WITH RESPECT TO NET WORKING TIME (Tn)		
LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3
on one or both knees	on a leg	standing	>±15°	0° ± 15°	0°	F > 2/3 di Tn	1/3 < F < 2/3 di Tn	F < 1/3 di Tn

Fig. 1. Ergonomic domains.

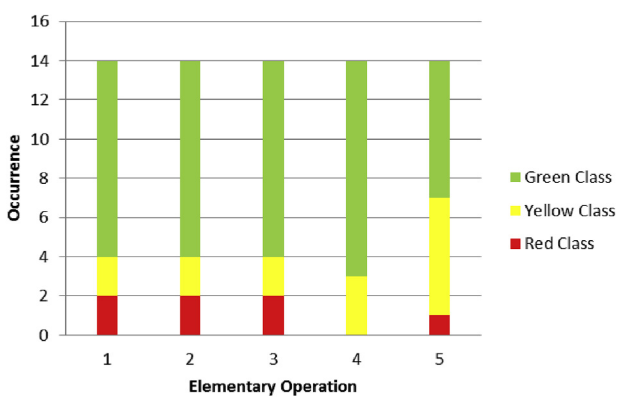

Fig. 2. Bar diagram – Elementary operations.

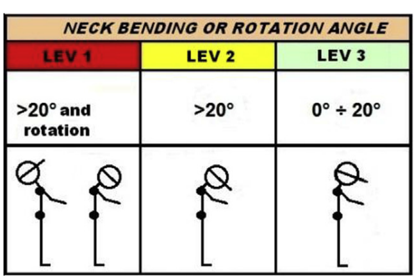

Fig. 3. Neck.

allowed identification of a lower limb field of analysis related to the leg. Three criticality areas have been identified with reference to the postures which can be assumed by an operator as follows:

(1) Stand position (lower criticality).
(2) Body weight on a leg (medium criticality).
(3) Body weight on one or both knees.

Level 1 and 2 come from RULA method while position on knee for level 3 is derived from REBA one. Fig. 4 visually represents these postures.

3.2.3. Stereotypy

Similarly to OCRA checklist, repetitiveness of operator's tasks have been assessed through the duration of the performed task.

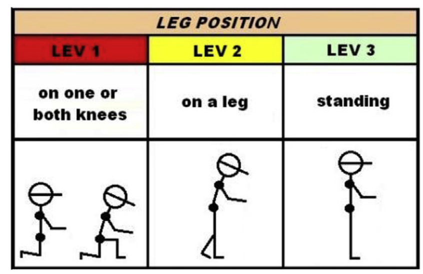

Fig. 4. Leg.

Such evaluation was performed with respect to the working time which can be evaluated as the shift time minus break intervals. Operator exposure to critical ergonomic operations was evaluated by the introduction of the following three groups:

(1) Task duration within the shift less than one-third of the working time (low criticality).
(2) Task duration within the shift between a third and two-thirds and of the working time (medium criticality).
(3) Task duration within the shift more than two-thirds of the working time (high criticality).

Fig. 5 shows the three classes and the levels associated with each of them.

3.3. Step 3 – score evaluation

An overall score is associated with a given operator according to the ergonomic assessment evaluation performed within the second step. The score is evaluated as follows:

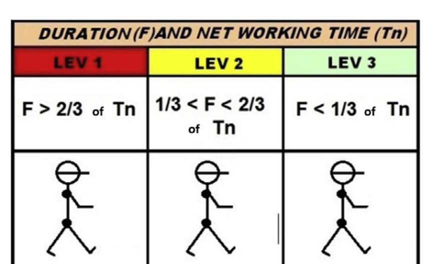

Fig. 5. Duration levels.

- ✓ A score is assigned to each color of the ergonomic field, as follows: 1 for Green – G, 2 for Yellow – Y, and 3 for Red – R;
- ✓ According to the ergonomic assessment and to the color, a partial ergonomic score (PES) is associated with each ith elementary operation by summing corresponding scores of each posture analyzed. For example, an elementary operation characterized by two red domains, four yellow domains and eight green domains has a PES value of $2 \cdot 3 + 4 \cdot 2 + 8 \cdot 1 = 22$
- ✓ The *overall ergonomic score* (OES) is associated with a given operator as follows:

$$OES = \frac{\sum_i PES_i}{3 \cdot NUM\_DOM \cdot NUM\_ELEM\_OPS}$$

where:

- ◦ $\sum_i PES_i$ is the sum of each score obtained for a single elementary operation;
- ◦ NUM_DOM is the number of selected ergonomic domains, i.e. 14 in our case;
- ◦ NUM_ELEM_OPS is the number of elementary operations selected in step 1 for a certain operator;
- ◦ $3 \cdot NUM\_DOM \cdot NUM\_ELEM\_OPS$ is the maximum score which can be obtained for the considered operator.

This procedure allows us to obtain a number belonging to the [0, 1] interval. OES summarizes the global ergonomic exposure of the given operator. For example, given an operator characterized by two elementary operations whose scores are 22 and 20, OES is equal to $\frac{22+20}{3 \cdot 14 \cdot 2} = 0.6$.

3.4. Step 4 – ergonomic assessment: summary

OES values are used to decide the timing and the changes to be applied to the line where the operator works. In particular, as shown in Table 3, four intervals of OES have been set; such intervals provide a useful indication of workplace gravity.

An explanation of the first lower zone is provided: with reference to a single elementary operation, it has been decided to define "acceptable ergonomics," a task characterized at maximum by:

- two yellow domains and twelve green domains: $OES = \frac{2 \cdot 2 + 12 \cdot 1}{3 \cdot 14 \cdot 1} = 0.38$;
- one red domain and thirteen green domains: $OES = \frac{1 \cdot 3 + 13 \cdot 1}{3 \cdot 14 \cdot 1} = 0.38$;

Consequently, through analysis of the value assumed by OES it is possible to state if corrective actions must be adopted and their timing.

In the case of intervention, i.e. if corrective actions are necessary, the priority is mainly given to elementary operations characterized by higher criticality. Such indications are provided by the scores obtained in the third step and immediately by the visual representation of gravity through the bar diagram developed during the second step. By shifting each ergonomic field towards the green color it is possible to reduce the gravity of the elementary operation and in general terms the overall ergonomic risk of the given operator.

Table 3
OES and assessment.

OES value	Operator status
$OES \leq 0.4$	Acceptable ergonomics
$0.4 < OES \leq 0.5$	Investigate: change may be needed
$0.5 < OES \leq 0.7$	Investigate: change soon
$OES > 0.7$	Immediately investigate and implement change

4. The assembly line

The test bed of the research methodology is a O-shaped assembly line for automotive components and the operators work on the outside of the line (Fig. 6).

The line is composed of 21 assembly stations with an average cycle time of about 25 s, which implies repetitive cyclic tasks. Of these, three are manually conducted by three operators identified by their respective station number, i.e. OP 10, OP 50 and OP 190. The operators are in charge of feeding the line with components assembled by automatic machines. More specifically, their main tasks consist of:

- feeding the respective workstation with the appropriate components;
- feeding the workplace with the components;
- supervising automatic machines.

Gravity chutes supply the workplace. Working tasks are generally performed in a standing position and require operators to handle light components grouped in heavy boxes (weight >30 Kg).

5. Results

Through the analysis of the EOs, it has been possible to proceed with the ergonomic assessment of the postures assumed by the operators. Since non-cyclic operations are involved into the assessment as well, more than one working shift can be necessary for analyzing 10 repetitions. This is not true for cyclic operations due to the short cycle time of the assembly line. Table 4 shows an extract of data analysis of 10 repetitions for two EOs with respective average and deviation of each ergonomic domain; for some of them (i.e. arm height, withdrawal and leg position) a statistical analysis of measures cannot be defined since the posture is univocally identified.

Fig. 7 shows an extract of the ergonomic assessment for operator 190.

A more detailed description of the elementary operations of OP 190 and related ergonomic domain assignment is provided in Table 5. For example, "Stud feeding" in station 110 has been assessed as very critical (i.e. red level) in the methodology. Arm height is in fact over the shoulders, in accordance with Fig. 1. Similarly, rotor feeding is performed by folding both knees and has been classified with a red color.

Overall outcomes of ergonomic assessment have been organized in diagrams in order to group postures belonging to gravity classes and visually represent the occurrences of each group. Each operator is characterized by a certain number of postures in green, yellow and red, as shown in Fig. 8.

More specifically:

- Postures in the green zone are 44, 109 and 138 for Op 10, Op 50 and Op 190 respectively.
- Postures in the yellow zone are 23, 26 and 52 for Op 10, Op 50 and Op 190 respectively.
- Postures in the red zone are 3, 5 and 6 for Op 10, Op 50 and Op 190 respectively.

Visually, a great number of postures have been classified in the

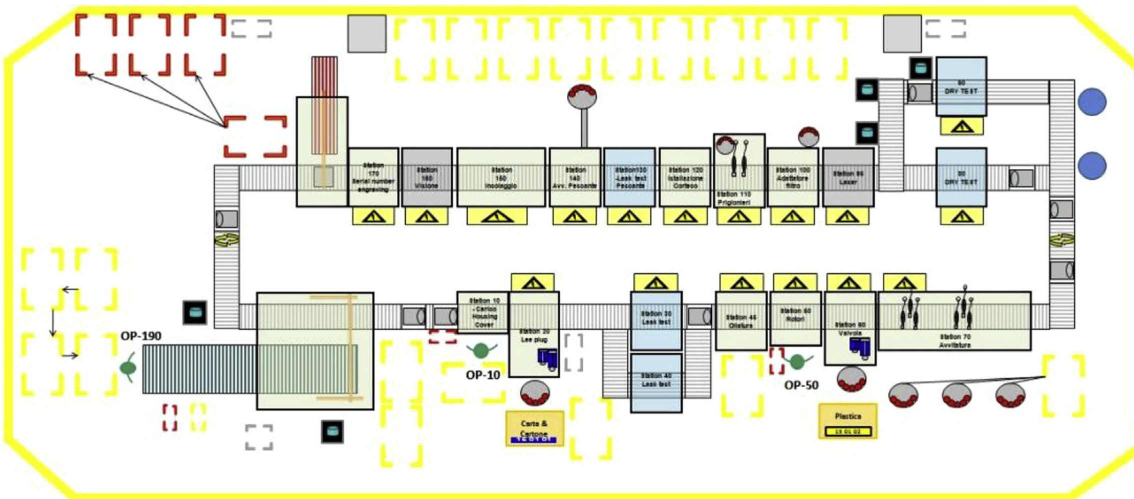

Fig. 6. Line layout.

Table 4
Extract of data analysis.

	EO 1			EO 2		
	Avg.	S.D.	Level	Avg.	S.D.	Level
Lumbar flexion angle	24.6°	2.5°	2	17.1°	1.5°	2
Wrist rotation angle	0.1°	3.1°	3	5.5°	0.5°	3
Arm height	Wrist height		3	At shoulders		2
Wrist rotation angle	22.5°	2.2°	3	105.5°	5.3°	2
Knees bending angle	1.5°	2.5°	3	1.2°	2.0°	3
Material withdrawal position	Stretching arms		2	Stretching arms		2
Rotation on x-angle	0	0	3	50.5°	1.2°	2
Walking steps	2.3	0.4	3	7.2	1.1	2
Carried load	0.3	0	3	0.2	0	3
Neck bending or rotation angle	0°	0°	3	0°	0°	3
Forearm rotation angle	21.2°	1.5°	3	110.2°	5.7°	2
Leg position	On one leg		2	On one leg		2
Wrist bending angle	10.7°	0.8°	2	5.7°	1.2°	2
Task duration divided by the net-working time	0.4	0.02	2	0.1	0.01	3

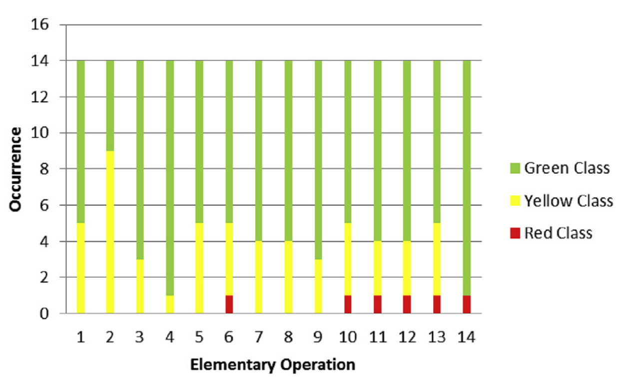

Fig. 7. Op 190 bar diagram.

green criticality class and almost the same number of postures are in the red zone. Postures in the yellow class are particularly predominant in Op 10, representing almost one-third of postures whereas Op 190 has twice as many yellow postures as Op 50. Such visual methodology suggests a qualitative ranking of the three operators with regard to ergonomic risk: Op 50 seems to have the lowest criticality, followed by Op 190 and Op 10.

A quantitative and more precise analysis can be conducted by the evaluation of the overall ergonomic score of each operator. Posture assignment of the ergonomic assessment allows us to obtain the following OES values: OP 10 with OES = 0.47; OP 50 with OES = 0.40; OP 190 with OES = 0.44.

According to OES values, OP 10 and OP 190 require changes to improve the performance of their production operations whereas OP 50 is characterized by an acceptable ergonomics. Improvements must be adopted first in elementary operations characterized by red and yellow ergonomic domains to reduce the overall criticality of the workplace. Such operations are visually identified in the matrixes of the ergonomic assessment by red and yellow colors.

Test case has also been used for testing inter- and intra-rater agreement performances of the proposed methodology through a dedicated statistical analysis of correlation indexes. More in details, ICC (2,1) was evaluated for intra-rater reliability while ICC (2,2) for inter-rater reliability as in Portney and Watkins (2009). The observers have been selected among internal managers with a previous experience and know-how in ergonomics and workplace organization. ICC (2,1) = 0.91 and ICC (2,2) = 0.93 are in the lower boundary for an high reliability in accordance to the cutoff values of Rheault et al. (1992).

6. Discussion

The effectiveness of the methodology has been proved by a

Table 5
Op 190 ergonomic assessment.

EO #	Operation description	TRUNK BENDING ANGLE			WAIST ROTATION ANGLE			ARM HEIGHT			WRIST ROTATION ANGLE			KNEES BENDING ANGLE			MATERIAL WITHDRAWAL POSITION			ROTATION ON AXIS ANGLE			WALKED STEPS NUMBER			CARRIED LOADS KILOS			NECK BENDING OR ROTATION ANGLE			FOREARM ROTATION ANGLE			LEG POSITION			WRIST BENDING ANGLE			TASK DURATION (F) WITH RESPECT TO NET WORKING TIME (Tn)		
		LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3	LEV 1	LEV 2	LEV 3
1	Finished product - withdrawal and depositing		2				3			3			3			3		2				3			3			3			3			3		2			2			2	
2	Shelves - withdrawal and depositing		2				3		2			2				3		2			2			2				3			3		2			2			2				3
3	Closing box of finished products		2				3		2				3			3			3			3			3			3			3			3			3		2				3
4	Finished products - Empty -> Full box sostitution			3			3			3			3			3			3			3			3		2				3			3			3			3			3
5	Station 100 - Adapters feeding (BL=>BF)			3			3		2				3			3			3			3			3		2			2			2				3		2				3
6	Station 110 - Stud feeding (BL=>BF)			3			3	1					3			3			3			3			3		2			2			2				3		2				3
7	Station 120 - Corteco feeding (GZ=>BF)			3			3		2				3			3			3			3			3			3		2			2				3		2				3
8	Station 140 - Screws feeding (BL=>BF)			3			3		2				3			3			3			3			3			3		2			2				3		2				3
9	Station 150 - Gasket feeding (GZ=>BF)			3			3			3			3			3			3			3			3			3		2			2				3		2				3
10	Station 50 - Rotor feeding (BL=>GZ)			3			3			3			3			3			3		2				3	1					3		2		1				2				3
11	Station 50 - Chute feeding			3			3		2				3			3			3			3			3	1					3		2				3		2				3
12	Station 10 - Cover feeding (BL=>GZ)			3			3			3			3			3			3		2				3	1					3		2				3		2				3
13	Station 10 - Chute feeding			3			3		2				3			3			3			3			3	1					3		2			2			2				3
14	Station 50 - Shelves feeding (Springs and plugs)			3			3			3			3			3			3			3			3	1					3			3			3			3			3

comparative analysis with the OCRA checklist. In particular, the OCRA checklist assigns a criticality class to each operator. The three operators are characterized by three different risk classes; checklist OCRA classifies the operators as follows:

- OP 10 is in the light yellow range, i.e. it is in a borderline zone with a very slight risk;
- OP 50 is characterized by an acceptable risk;
- OP 190 is characterized by a slight risk.

Vice versa, Table 6 shows the criticality assignment obtained through the proposed methodology.

If compared with the OCRA checklist, Op 50 remains the operator with the lowest ergonomic risk whereas Op 10 and 190 are inverted in criticality. Results are comparable since all the operators are characterized by low criticality classes with little change required. Different assignments of our methodology are owed to a positive lower limb assessment which generally lowers the overall criticality. Operators are not involved in tough operations related to such body areas, i.e. green levels are associated with lower limbs. Carried loads, however, are taken into account and assume great importance (i.e. red color) for the specific test case; this area is neglected by the OCRA checklist and could decrease the overall criticality evaluation. Similarly, ergonomic analyses of trunk and neck are included within the proposed assessment and show medium criticality (i.e. yellow color); these aspects are also neglected in the OCRA checklist.

On the basis of the OCRA assessment, nothing more can be said about class assignment; considerations about critical postures cannot be conducted, i.e. in this case it is not possible to identify directly which are the operations generating higher criticality without revisiting the ergonomic assessment. In this context, selection of critical postures is more time- and resource-consuming with respect to the proposed methodology.

In this sense, the proposal reveals its effectiveness for a fast detection of uncomfortable postures: as results from Fig. 7, OP 190 has discomfort in 6 EOs (i.e. 6 and from 10 to 14) generating an high OES value. The visual management approach provides a set of visual maps to guide the analyst through the postural assessment in association with the OES, filling the gap which has been discussed in section 3. Such analysis is possible for each of the selected domains which cover the entire body of an operator, immediately highlighting criticalities which are combined in the OES. Postures are immediately detected in Table 5 at the corresponding rows. Vice versa, postures detection through traditional ergonomic assessment (e.g. OCRA) is not possible without tracing back the entire analysis. In this sense, the methodology can also be applied to accelerate possible redesign procedures of manufacturing lines in case of ergonomic criticalities through a more immediate and easier approach with respect to OCRA method where ease is highlighted by high values of correlation coefficients (see section 5). Such reliability of results can addressed to the adoption of well-assessed and known methods which have been combined together to obtain the proposed full body methodology.

7. Conclusions

This work presents a visual and easy-to-use approach to support a full body postural assessment. After analysis of ergonomic approaches described in the literature, the study selected a set of ergonomic domains and related ranges to design a new ergonomic full body assessment based on visual management techniques. The method has been tested on simple manufacturing cycles and fast tasks where elementary operations can be generally associated with an elementary movement characterizing a muscular domain.

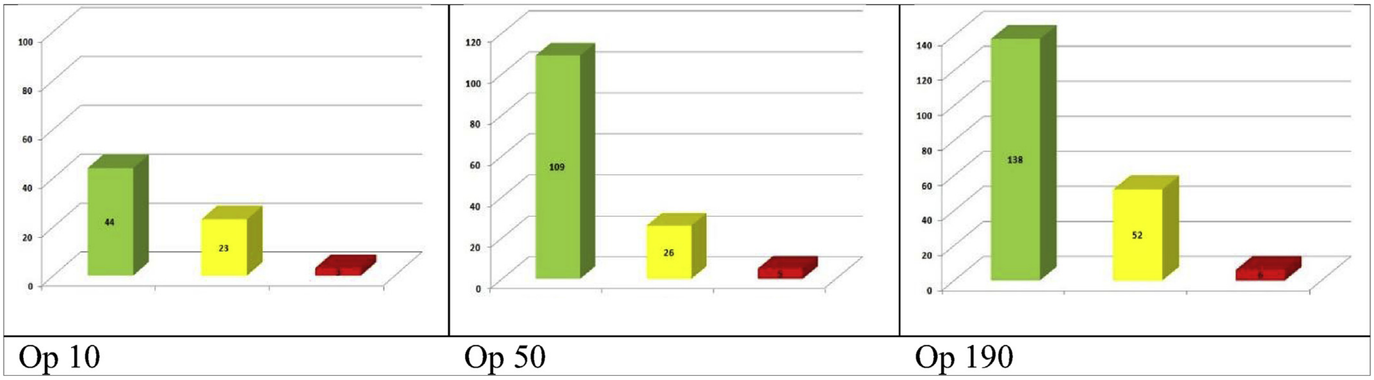

Fig. 8. Results of ergonomic assessment: the occurrence of each gravity class per each operator.

Table 6
Criticality assignment.

OES value	Operator status	OPs
$OES \leq 0.4$	Acceptable ergonomics	OP 50, OES = 0.40
$0.4 < OES \leq 0.5$	Investigate: change may be needed	OP 190, OES = 0.44 OP 10, OES = 0.47
$0.5 < OES \leq 0.7$	Investigate: change soon	
$OES > 0.7$	Immediately investigate and implement change	

For the specific test case, a comparison with the OCRA checklist evidenced the effectiveness of the methodology for rapid data and criticality analysis. The support of visual management can provide immediate and accessible feedback about the ergonomic assessment of each operator, focusing on interventions to reduce criticality. Differently from the OCRA checklist, identification of causes generating a certain criticality is simplified by the adoption of a semaphore where the red color suggests postures to be investigated and subjected to corrective actions. The overall score provides an indicator about the state of the operators in terms of ergonomic quality, suggesting an intervention order. The proposed method can be used for fast recognition of critical postures, similarly to the OCRA checklist, which, according to Occhipinti and Colombini (2005), is a promising initial framework, as it is simple to apply and suitable for an initial screen of repetitive tasks.

References

Andreoni, G., Mazzola, M., Ciani, O., Zambetti, M., Romero, M., Costa, F., Preatoni, E., 2009. Method for movement and gesture assessment (MMGA) in ergonomics. In: International Conference on Digital Human Modeling, pp. 591–598.
Balasubramanian, V., Adalarasu, K., Regulapati, R., 2009. Comparing dynamic and stationary standing postures in an assembly task. Int. J. Ind. Ergon. 39, 649–654.
Bao, S., Mathiassen, S.E., Winkelly, J., 1996. Ergonomic effects of a management based rationalization in assembly work – a case study. Appl. Ergon. 27 (2), 89–99.
Bao, S., Winkel, J., Mathiassen, S.E., Shahnavaz, H., 1997. Interactive effect of ergonomics and production engineering on shoulder-neck exposure – a case study of assembly work in China and Sweden. Int. J. Ind. Ergon. 20, 75–85.
Battini, D., Faccio, M., Persona, A., Sgarbossa, F., 2011. New methodological framework to improve productivity and ergonomics in assembly system design. Int. J. Ind. Ergon. 41, 30–42.
Battini, D., Persona, A., Sgarbossa, F., 2014. Innovative real-time system to integrate ergonomic evaluations into warehouse design and management. Comput. Ind. Eng. 77, 1–10.
Brown, R., Li, G., 2003. The Development of Action Levels for the Quick Exposure Check (QEC) System, Contemporary Ergonomics. Taylor & Francis, pp. 38–43.
Burdorf, A., 1995. Reducing random measurement error in assessing postural load on the back in epidemiologic surveys. Scand. J. Work Environ. Health 21, 15–23.
Carey, E.J., Gallwey, T.J., 2002. Evaluation of human postures with computer aids and virtual workplace designs. Int. J. Prod. Res. 40 (4), 825–843.
Cecchini, M., Colantoni, A., Massantini, R., Monarca, D., 2010. The risk of musculoskeletal disorders for workers due to repetitive movements during tomato harvesting. J. Agric. Saf. Health 16 (2), 87–98.
Cheshmehgaz, Haron H., Kazemipour, F., Desa, M.I., 2012. Accumulated risk of body postures in assembly line balancing problem and modeling through a multi-criteria fuzzy-genetic algorithm. Comput. Ind. Eng. 63, 503–512.
Chiasson, M.-È., Imbeau, D., Aubry, K., Delisle, A., 2012. Comparing the results of eight methods used to evaluate risk factors associated with musculoskeletal disorders. Int. J. Ind. Ergon. 42, 478–488.
Cimino, A., Longo, F., Mirabelli, G., 2009. A multimeasure-based methodology for the ergonomic effective design of manufacturing system workstations. Int. J. Ind. Ergon. 39 (2), 447–455.
Colombini, D., Occhipinti, E., Grieco, A., 2002. Risk Assessment and Management of Repetitive Movements and Exertions of Upper Limbs: Job Analysis, OCRA Risk Indices, Prevention Strategies and Design Principles. Elsevier Science Ltd, London.
Cort, J.A., Stephens, A., Potvin, J.R., 2006. A biomechanical and psychophysical examination of fastener initiations in automotive assembly. Int. J. Ind. Ergon. 36, 837–845.
d'Errico, A., Gore, R., Gold, J.E., Park, J.-S., Punnett, L., 2007. Medium- and long-term reproducibility of self-reported exposure to physical ergonomics factors at work. Appl. Ergon. 38, 167–175.
Drinkaus, P., Sesek, R., Bloswick, D., Bernard, T., Walton, B., Joseph, B., 2003. Comparison of ergonomic risk assessment outputs from rapid upper limb assessment and the strain index for tasks in automotive assembly plants. Work 21 (2), 165–172.
Dul, J., de Vries, H., Verschoof, S., Eveleens, W., Feilzer, A., 2004. Combining economic and social goals in the design of production systems by using ergonomics standards. Comput. Ind. Eng. 47, 207–222.
Dul, J., Neumann, W.P., 2009. Ergonomics contributions to company strategies. Appl. Ergon. 40, 745–752.
Enomoto, A., Yamamoto, N., Suzuki, T., 2012. Automatic estimation of the ergonomics parameters of assembly operations. CIRP Ann. Manuf. Technol. 62, 13–16.
Falck, A., Rosenqvist, M., 2014. A model for calculation of the costs of poor assembly ergonomics (part 1). Int. J. Ind. Ergon. 44, 140–147.
Ferguson, S.A., Marras, W.S., Allread, W.G., Knapik, G.G., Vandlen, K.A., Splittstoesser, R.E., Yang, G., 2011. Musculoskeletal disorder risk as a function of vehicle rotation angle during assembly tasks. Appl. Ergon. 42, 699–709.
Genaidy, A.M., Al-Shed, I.A.A., Karwowsk, I.W., 1994. Postural stress analysis in industry. Appl. Ergon. 25, 77–87.
Gooyers, C.E., Stevenson, J.M., 2011. The impact of an increase in work rate on task demands for a simulated industrial hand tool assembly task, School of Kinesiology and Health Studies, Queen's University. I Int. J. Ind. Ergon. 42, 80–89.
Graham, R.B., Sheppard, P.S., Almosnino, S., Stevenson, J.M., 2012. Dynamic spinal stability and kinematic variability across automotive manufacturing work shifts and days. Int. J. Ind. Ergon. 42, 428–434.
Guimarães, L.B., Ribeiro, J.L.D., Renner, J.S., 2012. Cost-benefit analysis of a socio-technical intervention in a Brazilian footwear company. Appl. Ergon. 43, 948–957.
Hignett, S., McAtamney, L., 2000. Rapid entire body assessment (REBA). Appl. Ergon. 31 (2), 201–205.
Jones, T., Kumar, S., 2007. Comparison of ergonomic risk assessments in a repetitive

high-risk sawmill occupation: saw-filer. Int. J. Ind. Ergon. 37, 744–753.
Joseph, C., Imbeau, D., Nastasia, I., 2011. Measurement consistency among observational job analysis methods during an intervention study. Int. J. Occup. Saf. Ergon. 17 (2), 139–146.
Kazmierczak, K., Mathiassen, S.E., Forsman, M., Winkel, J., 2005. An integrated analysis of ergonomics and time consumption in Swedish 'craft-type' car disassembly. Appl. Ergon. 36, 263–273.
Kee, D., Chung, M.K., Kim, J.-H., 2011. Legal system and its effect for prevention of work-related musculoskeletal disorders in Korea. Int. J. Ind. Ergon. 41, 224–232.
Kee, D., Karwowski, W., 2007. A comparison of three observational techniques for assessing postural loads in industry. Int. J. Occup. Saf. Ergon. 13 (1), 3–14.
Kihlberg, S., Medbo, P., Mathiassen, S.E., Winkel, J., 2002. A case study evaluating the ergonomic and productivity impacts of partial automation strategies in the electronics industry. Int. J. Prod. Res. 40 (16), 4059–4075.
Landau, K., Rademacher, H., Meschke, H., Winter, G., Schaub, K., Grasmueck, M., Moelbert, I., Sommer, M., Schulze, J., 2008. Musculoskeletal disorders in assembly jobs in the automotive industry with special reference to age management aspects. Int. J. Ind. Ergon. 38, 561–576.
Lavender, S.A., Oleske, D.M., Andersson, G.B.J., Morrissey Kwasny, M.J., 2006. Low-back disorder risk in automotive parts distribution. Int. J. Ind. Ergon. 36, 755–760.
Mirka, G.A., Smith, C., Shivers, C., Taylor, J., 2001. Ergonomic interventions for the furniture manufacturing industry. Part I – lift assist devices. Int. J. Ind. Ergon. 29, 263–273.
Neumann, W.P., Medbo, L., 2010. Ergonomic and technical aspects in the redesign of material supply systems: big boxes vs. narrow bins. Int. J. Ind. Ergon. 40, 541–548.
Occhipinti, E., Colombini, D., 2005. The Occupational Repetitive Action (OCRA) Methods: OCRA Index and OCRA Checklist, Handbook of Human Factors and Ergonomics Methods. CRC.
Otto, A., Scholl, A., 2011. Incorporating ergonomic risks into assembly line balancing. Eur. J. Oper. Res. 212, 277–286.
Ouellet, S., Vezina, N., 2014. Work training and MSDs prevention: contribution of ergonomics. Int. J. Ind. Ergon. 44, 24–31.
Öztürk, N., Esin, M.N., 2011. Investigation of musculoskeletal symptoms and ergonomic risk factors among female sewing machine operators in Turkey. Int. J. Ind. Ergon. 41 (6), 585–591.
Portney, L., Watkins, M., 2009. Foundations of Clinical Research: Applications to Practice. Pearson Prentice Hall, New Jersey.
Rheault, W., Albright, B., Byers, C., Franta, M., Johnson, A., Skowronek, M., 1992. Intertester reliability of the cervical range of motion device. J. Orthop. Sports Phys. Ther. 15 (3), 147–150.
Roman-Liu, D., 2014. Comparison of concepts in easy-to-use methods for MSD risk assessment. Appl. Ergon. 45, 420–427.
Russell, S.J., Winnemuller, L., Camp, J.E., Johnson, P.W., 2007. Comparing the results of five lifting analysis tools. Appl. Ergon. 38 (1), 91–97.
Shuval, K., Donchin, M., 2005. Prevalence of upper extremity musculoskeletal symptoms and ergonomic risk factors at a Hi-Tech company in Israel. Int. J. Ind. Ergon. 35 (6), 569–581.
Spielholz, P., Bao, S., Howard, N., Silverstein, B., Fan, J., Smith, C., Salazar, C., 2008. Reliability and validity assessment of the hand activity level threshold limit value and strain index using expert ratings of mono-task jobs. J. Occup. Environ. Hyg. 5 (4), 250–25.
Sundin, A., Christmansson, M., Larsson, M., 2004. A different perspective in participatory ergonomics in product development improves assembly work in the automotive industry. Int. J. Ind. Ergon. 33, 1–14.
Takala, E.-P., Pehkonen, I., Forsman, M., Hansson, G.-Å., Mathiassen, S.E., Neumann, W.P., Sjøgaard, G., Veiersted, K.B., Westgaard, R.H., Winkel, J., 2010. Systematic evaluation of observational methods assessing biomechanical exposures at work. Scand. J. Work Environ. Health 36 (1), 3–24.
Thun, J., Lehr, C.B., Bierwirth, M., 2011. Feel free to feel comfortable—an empirical analysis of ergonomics in the German automotive industry. Int. J. Prod. Econ. 133, 551–561.
van Rijn, R.M., Huisstede, B., Koes, B.W., Burdorf, A., 2009. Associations between work-related factors and the carpal tunnel syndrome—a systematic review. Scand. J. Work Environ. Health 35 (1), 19–36.
van Rijn, R.M., Huisstede, B., Koes, B.W., Burdorf, A., 2010. Associations between work-related factors and specific disorders of the shoulder – a systematic review of the literature. Scand. J. Work Environ. Health 36 (3), 189–201.
Vignais, N., Miezal, M., Bleser, G., Mura, K., Gorecky, D., Marin, F., July 2013. Innovative system for real-time ergonomic feedback in industrial manufacturing. Appl. Ergon. 44 (4), 566–574.
Xiao, G.-B., Dempsey, P., Lei, L., Ma, Z.-H., Liang, Y.-X., 2004. Study on musculoskeletal disorders in a machinery manufacturing plant. J. Occup. Environ. Med. 46 (4), 341–346.