Innovative real-time system to integrate ergonomic evaluations into warehouse design and management

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ABSTRACT

The present paper introduces an innovative full-body system for the real-time ergonomics evaluations of manual material handling in warehouse environments, where all parts of the body are interested during the activities execution. The system is based on inertial sensors with integrated compensation of magnetic interference and long wireless connection that permit its use also in heavy industrial applications. A specific set of tools has been developed in order to elaborate the collected motion data and give real-time evaluation and feedback of ergonomics based on the most used methodologies and extended with others advanced ad hoc tools, such as hands positions analysis, travel distance, time and methods collection calculations. The system has been applied to two different warehouses both for the re-design of the storage area and successively management of the typical warehousing activities, such as picking, packing and others, reducing the risk of musculoskeletal disorders and simultaneous increasing of productivity of systems.

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1. Introduction

In the modern global supply chain context, more and more attention has been paid to the warehousing aspects for multiple reasons. Even if stocking facilities are extremely necessary to solve the traditional supply chain imbalances, they are seen as cost centers, both for blocked investment capitals and for high-human resources consume.

Moreover, global competition and markets extreme variability have led societies to order, purchase, produce and sell smaller and smaller quantities of products, doing this very often.

Furthermore, the optimization of productive and assembly systems also involved a distinct separation between the production/ assembly activities and the preparation of components and semi-finished products supplying these systems.

All this pushed societies and the academic world to pay more attention to the design and management of warehouses, both for finished and work in process products.

In these stocking systems, picking activities are very important as highlighted in literature (Coley et al., 1996; Grosse, Glock, & Jaber 2013) because of an important expenditure of human resources, between 50% and 75%.

In the last years, due to the high incidence of manual activities in the warehousing operations, such as lifting, picking, sorting, pushing, pulling and others, the well-being of the operators has been widely studied. van Reenen et al. (2008) have argued that the future long-term muscular pain, such as musculoskeletal disorders (MSDs), depends on the discomfort felt by the warehouse operators. Generally, MSDs caused by manual tasks represent a large part of all work-related MSDs (Burgess-Limerick, 2007; Euzenat, 2010) and are a central issue for public health (Martinelli, 2010).

As well demonstrated in Battini, Faccio, Persona, and Sgarbossa (2011), it is important to include also the ergonomics evaluations in the human operations analysis due to the strictly interaction between productivity and motion efficiency and operational safety.

A lot of methods and tools have been developed to help the engineering and managers estimate the incorrect postures and related activities for several industrial contexts.

The particular aspects of the warehousing activities which involve all body parts and the wide differences between each of them require the use of more than one ergonomics evaluation method in order to have a global accurate assessment.

Several of these ergonomics evaluation methods includes OCRA, NIOSH lifting equation, RULA, REBA, HAL-TLV, OWAS, LUBA, OCRA, Strain index, SNOOK tables (Andreoni et al., 2009).

Each of them has different features and considers different aspects useful for ergonomics evaluations, as explained in Fig. 1 and Table 1.

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    E-mail addresses: daria.battini@unipd.it (D. Battini), alessandro.persona@unipd.it (A. Persona), fabio.sgarbossa@unipd.it (F. Sgarbossa).

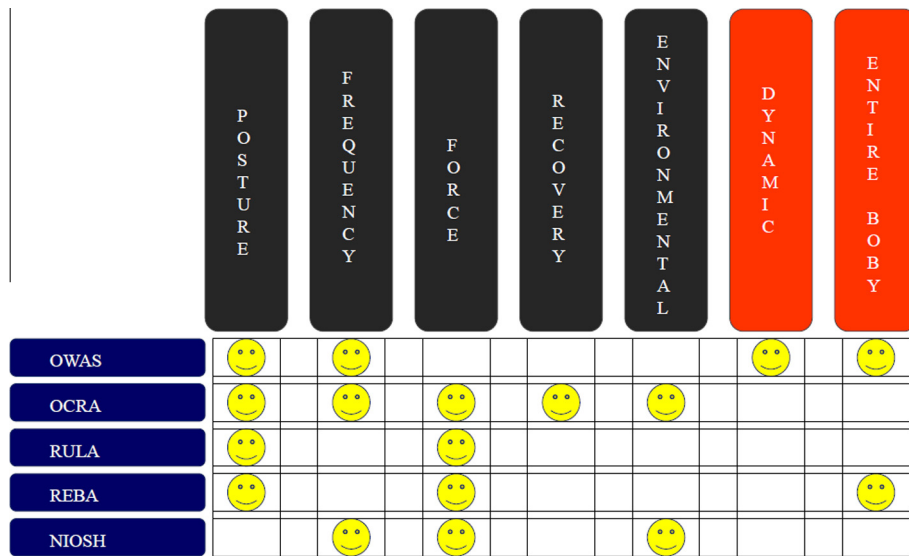|	POSTURE	FREQUENCY	FORCE	RECOVERY	ENVIRONMENTAL	DYNAMIC	ENTIRE BODY
OWAS	☺	☺				☺	☺
OCRA	☺	☺	☺	☺	☺		
RULA	☺		☺				
REBA	☺		☺				☺
NIOSH		☺	☺		☺		

Fig. 1. Main ergonomics evaluation methods and their characteristics.

Table 1
Classification of the most used ergonomics methods.

Method	When	Focus	References
BORG SCALE	Perceived exertion evaluation	Simple method to measure physical activity intensity levels	Borg (1970)
OWAS Ovako Working Analysis System	Fast postural targeting	Work-related disorders on 4 basic body portion without detail on upper limb, verifying the frequency and the time taken in each posture.	Karhu et al. (1977)
RULA Rapid Upper Limb Assessment		Fast evaluation of upper body members constraints	McAtamney and Corlett (1993)
REBA Rapid Entire Body Assessment		Fast evaluation of the whole body and highlight the fast change of postures	Hignett and y McAtamney (2000)
Strain index	Repetitive movements evaluation	Upper limb repetitive movement equation	Moore and y Garg (1995)
OCRA Occupational Repetitive Action		Upper limb repetitive movements evaluation check list	Colombini et al. (2002)
Snook and Ciriello	Manual lifting evaluation	Evaluation tables of maximum acceptable weights and forces".	Ciriello and Snook (1978)
NIOSH National Institute of Occupational Safety and Health		Lifting equation that define the RWL: Recommended Weight Limit	Niosh (1981)

Moreover the ergonomics assessment methods can be applied using different tools, which can be divided into self-report, observational tools, virtual simulations and direct measurements with different limitations, advantages and applications (David, 2005; Honglun, Shouqian, & Yunhe, 2007; Li & Buckle, 1999).

Self-reports involve worker diaries, interviews and questionnaires. Having a relevant subjective aspect due to the different possible interpretation, comprehension and perception of fatigue by the operators, their uses are limited and the results need to be understood and validated.

The observational tools introduce some predefined sheets to be used during the direct observation or using the video-records. Typically, these are composed by several tables where the evaluators remark the operators' postures during the execution of the analyzed tasks. The detail of the analysis, as part of the body under evaluation, depends on the methodology used for the ergonomics assessment. The results are typically defined as evaluation indices which are compared successfully to threshold values. These kinds of tools are widely used in very different situations, but they are very time consuming and the scoring system is questionable, too.

The virtual simulations tools are typically 3D-CAD software where human models are constructed and their activities are simulated. Several of these include some ergonomics evaluation methods as internal tools. In this case, high experience in the 3D modeling is necessary in order to make the model in reasonable time. Moreover only few methodologies are implemented in these software. Consequently, these aspects limit the use of these tools just in very few cases.

Finally, in the last years, direct measurement tools are developed introducing real-time posture data collection using sensors placed on the operators under analysis (Bernmark & Wiktorin, 2002; Freivalds, Kong, You, & Park, 2000; Radwin & Lin, 1993). As discussed by David (2005) these methods require a complex and cost-intensive hardware setup and a lot of effort to analyze and interpret recorded data in real-time. As a consequence, the ergonomic evaluation of the directly assessed behavior has to be performed offline.

On the other hand, Mullineaux, Underwood, Shapiro, and Hall (2012) and Vignais et al. (2013) have demonstrated that real-time postural evaluation with simultaneous feedback to the operator provides benefits in practice.

However, these tools present several important limitations: first of all they are applied only in a well-controlled environment, such as a laboratory; then they are limited to the upper body and RULA methodology is the only one applied with all its limitations defined in previous researches, such as some angle thresholds, upper arm abduction or neck twist.

For all these reasons, an innovative integrated system has been developed in order to combine the real-time motion data collection and their ergonomics evaluation. Moreover the analysis of data is complete with the most relevant information about the tasks execution, such as time and methods.

2. Purpose of the research

The objective of this research is to introduce and discuss a new integrated system for the real-time ergonomics evaluation and task analysis. It has been applied in several real case studies inside different warehouses where, as discussed before, the operators perform different tasks that required the movement of all parts of the body.

Its use has been demonstrated to be useful in helping the engineers into the complete design and management of logistics systems, thanks to some extended data analysis tools, and, with the use of small portable screens, in assisting the workers with feedback of the main information about the posture in real-time.

This system is a full-body motion capture system (MoCap system), within 17 inertial measurement units, integrated with several data-analysis tools developed by the authors, for the real-time ergonomics assessment based on the most used methodologies, such as OWAS, OCRA, RULA and others, that were developed ad hoc. The use of this kind of motion capture system is due to its more flexibility compared to the systems with optical sensors, because in this case no camera is needed, that means more freedom and wide application field, according to previous researches (Breen, Nisar, & Olaighin, 2009; Jayaram, Jayaram, Shaikh, Kim, & Palmer, 2006; Ray & Teizer, 2012).

The operators' movements are recorded by the motion capture system and linked to a full-body biomechanical model on which the selected ergonomics evaluation methodology is continuously computed. The use of 3D CAD modeling and the development of ergonomics indices with colored measurement scaling allow a real-time feedback. Information about the load can be added in post processing phase and included in the final evaluation.

Moreover, the system is completed with the introduction of a useful software tool developed for the real-time collection of activities information, such as kind of task, time and methods to execute the activity.

This allow to highlight the most critical movements and their related activities with two main advantages: first, it assists the engineers and managers in the designing and management with an integrated and win–win approach reaching benefits both for the wellness of operators and directly for the productivity, as demonstrated in Battini et al. (2011), furthermore the real-time feedback given to the workers involves in a general improvement of ergonomics during the manual task execution, as demonstrated also by Vignais et al. (2013).

3. Instrumentations and ergonomic evaluation tools

In this section, the integrated system and all its parts are presented in detail, illustrating their main characteristics and operation. It has been divided into hardware sub-system for the movements' data collection and software sub-system for the real-time data processing based on full-body biomechanical model. This is necessary because the warehousing activities require the movement of full-body, therefore more than one ergonomics evaluation methodologies is necessary to give a comprehensive analysis. These methods are briefly introduced in order to explain the required data and their elaboration for real-time assessment.

3.1. Hardware sub-system for the data collection

The primary data regarding the full-body movements are collected using a commercial inertial motion capture system, developed by Animazoo (UK), called IGS-180i which includes also a magnetic compensation to capture in locations previously out-of-bounds for inertial systems, such as factories, warehouses, assembly and production lines.

The system is composed by 17 IMUs, placed on a light full-body suit (total weight is 1.5 kg), working on an inertial update rate of 500 Hz with a maximum angular rate of 1200°/s and 6 degrees of freedom for each sensor (Fig. 2). The dimensions of IMUs are 5.07 cm × 1.45 cm × 0.92 cm, with a weigh of about 11 g for each sensor. They are linked to a light and small portable multi-processing unit (MPU) which, thanks to a WIFI connection up to more than 50 m, sends the data to the personal computer for the real-time processing. The magnetic interferences are solved with an advanced compensation developed for each IMU, reaching very accurate resolution degrees.

Finally, it is very flexible, due to its adaptability to very different operators and application environments, from laboratory to warehousing or production-assembly systems and it is very quick to use, with very low setup time, up to 10 min.

The available motion data are easy to be processed and they regard both all the body joint angles and body segments orientations and positions, thanks to the pipeline procedure for defining the correct human skeleton.

3.2. Software sub-system for the data processing

Firstly, a full-body biomechanical model (Fig. 2) is built from a special tool of hardware system to connect the collected motion data in the virtual environment where the ergonomics evaluations are performed.

The data regarding joints angles and body segment positions are processed by specific real-time tools, developed according to the main ergonomics assessment methodologies, such as RULA,
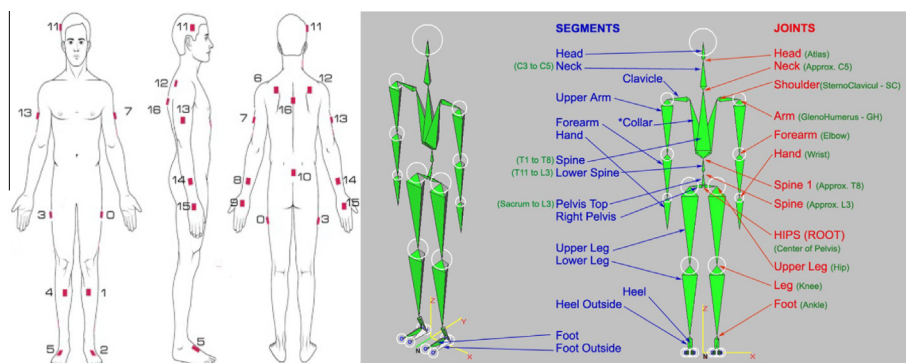

Fig. 2. Positions of IMUs and relative biomechanical model.

OWAS, OCRA and Lifting Index (LI). Moreover, other motion data analyses have been introduced in order to analyze more deeply other ergonomics aspects, such as hands position or travelled distance during the execution.

The software sub-system is integrated with the hardware one following the conceptual logic scheme reported in Fig. 3.

Firstly, two based units, called Connection Management Unit and MoCap Suit Management Unit, guarantee the correct and accurate operating of the hardware sub-system, alerting if any problems occur. (See Fig. 4–8).

The main part of the software sub-system concerns the real-time tools for the ergonomics evaluations. Here the Data Collection and Analysis Unit receives all the pre-processed data necessary to perform the real-time ergonomic evaluations.

Then the user can select the best suitable method thanks to the Selection Methods Module, according to the specific limitations of each ergonomics assessment method.

In fact, as explained in Andreoni et al. (2009), it is well known that each methodology has some specific limitations and applicability, these limitations can be divided into two main groups.

The first one contains the general limitations, for example regarding field of application, body part analysis, consideration of psychosocial factors, requirement of well-trained observer, use of semi-quantitative multipliers or risk factors and others.
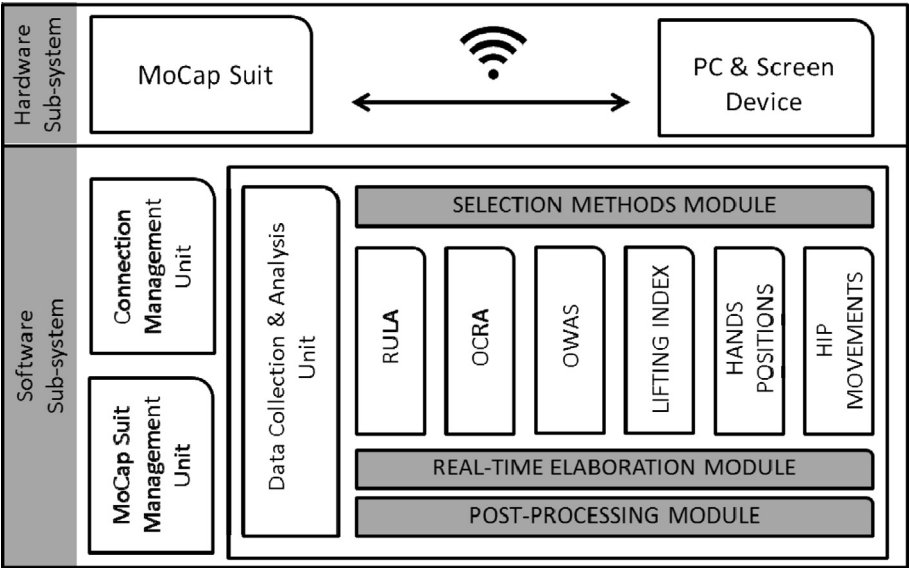

Fig. 3. Logical scheme of the integrated real-time system.

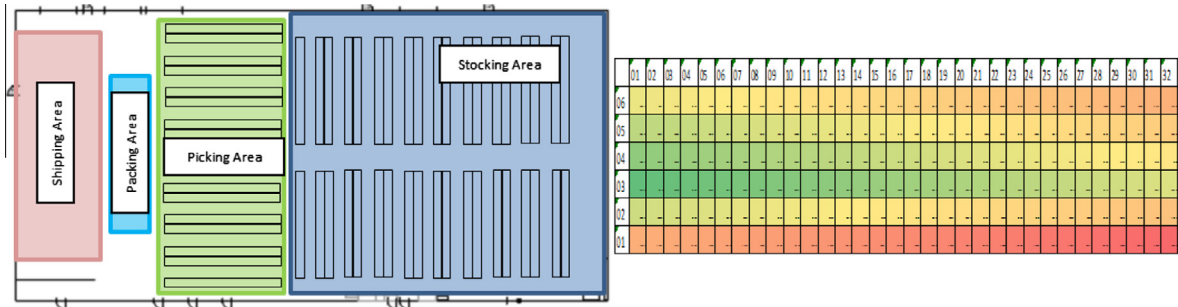Fig. 4. Storage areas and some pictures of warehousing activities.

Fig. 5. New storage area definition and class-based storage assignment inside a shelf.
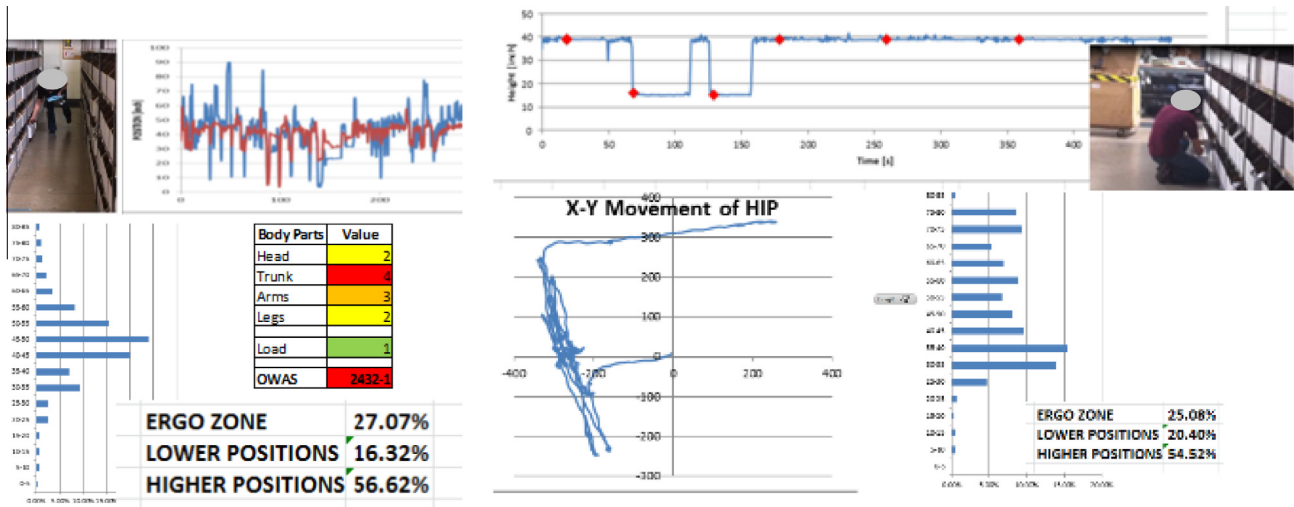
Fig. 6. Some pictures of the application of the integrated system.

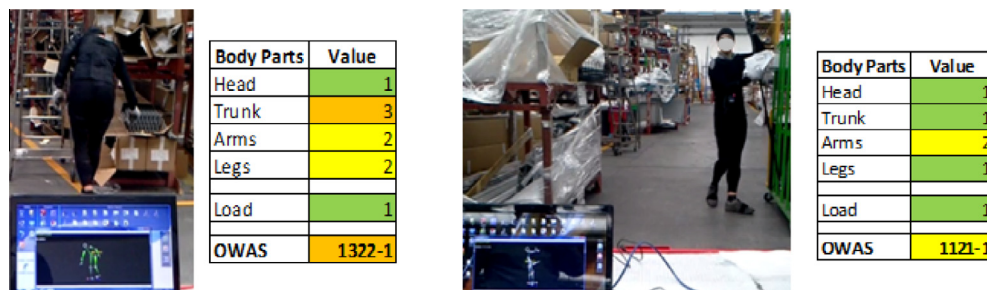**Fig. 7.** Warehouse map and some pictures of storage location and picking activity.

Fig. 8. Some applications of developed tools in case 2.

The second group of limitations is directly related to measurements of body parts, such as angles, to evaluations of several postures, such as lateral bending, and to operations performing, for example simultaneous use of arms.

For these reasons, the Selection Methods Module allows the user to select the most suitable tools for each application considering the first group of limitations, thanks to some instructions included in the module.

Moreover, for each tool, some threshold parameters are introduced to inform through some alarms when the selected method could fail or if it collects data out of its limits. Then the users can choose whether to consider or not these data during the real-time analysis (Real-Time Elaboration Module) or to elaborate them in the post-processing phase (Post-Processing Module).

In detail, using the RULA method, the analyzed joint angles are located into the upper body, as head, trunk, upper arms, forearms and hand positions. Other considerations, such as the muscle-use, are deduced by the task execution (Vignais et al. 2013) using the specific tasks' time and methods analysis tool. Some examples of threshold parameters are some angles regarding upper arm abduction or neck twist where RULA proposes only some qualitative adjustments of the score. The tool underlines when these situations happen, giving an alarm but also calculating a tentative evaluation according to RULA guidelines.

Moreover, the system permits to define the awkward postures for the estimation of OCRA index in a real accurate way, similar for the RULA tool. In fact these parameters associated to the posture are very hard to assess by the evaluators and often their impacts on the final OCRA score are relevant (Colombini, Occhipinti, & Grieco, 2002).

One of the main limitations of the awkward posture parameter in OCRA index regards the lack of evaluation of head, neck and trunk position. As developed for the RULA tool, also in this case, the system identifies with an alarm the data concerning unnatural

head, neck and trunk position. However, the system introduces a settable multiplier factor for considering also these awkward postures.

OWAS (Karhu, Kansi, & y Kuorinka, 1977) requires general information about head, trunk, arms and legs in order to give full-body ergonomics evaluation. In the latter method, some addiction calculations are needed in order to model the different postures, such as the positions of the arms, under or above the heart or the positions of legs. Also in this case, the computations are performed in real-time in function of the raw data collected by the motion capture system.

OWAS method is very simple to apply but, on the other hand, it also presents several limitations to the missing evaluation of some postures, such as lateral bending, trunk extension, sit or lie on the floor, crawl. In this case, following the guidelines given by the developers of OWAS method, some additional categories are introduced in the tools in order to include these postures, too. However, an alarm is set in order to advise the use of these new categories.

Finally, the Lifting Index (LI) is estimated thanks to the processed data about the position of the hands, integrated with a specific software tool that permits to associate the moved load to each movement.

Also for Lifting index, the real-time tool considers several limitations such as single hand lifting, carrying, type of grip and others. As done for the other tools, the system highlights these situations and gives the user the opportunity to set some additional factors to evaluate these postures.

Furthermore, as discussed in the introduction, the system completes the analysis also including others data computations tools, which have been very useful during the application in the real-case studies.

For example, some of these regard the vertical position of hands, giving a percentage of time spent in different heights, or distance of the hands from the center of the body, applied to give a score of efficiency of operation.

Other elaborated motion data are the horizontal movements of the hips used to estimate the total travelled distance during a specific task, or the vertical movements of the hips that indicate eventual kneeling or lowering.

Finally, the recovery time can be estimated when the motion data are constant enough for an appropriate time defined a priori.

For each technique, the biomechanical model gives the required data for the real-time computations, as indicated in Table 2, using specific tools developed by the authors for each ergonomics evaluation method. As well known, the before mentioned ergonomic methods need high number of observations about different parts of body and global postures.

All these indices can be shown to the operators and/or the engineers using a typical colored scaling in portable screens or personal computers, giving a feedback useful for real-time ergonomic improvements or global system analysis. (See Tables 3 and 4).

Another innovative aspect of this research is the development of a specific tool that permits to define the executed activities and measure their duration in a real-time way, saving some particular notes, such as moved loads and considerations about their execution and the working environment. This is easily used by the evaluators simultaneously during the motion data collection and its application permits to connect the different ergonomics parameters to the real task performed.

3.3. Considerations about the new integrated system

Recent researches have demonstrated the potential of motion capture systems and their application for the ergonomics evaluations (Vignais et al. 2013), but the presented contributions have still important restrictions. This innovative system permits to cover these limitations.

Firstly regarding the number of used IMUs sensors: the new system allows a full-body data collection with 17 sensors. Then it permits the application of many ergonomics evaluation methods and the analysis of activities which interest all the body, typically in warehouse environment or generally speaking in the manual material handling. Additionally, the advanced compensation extends the use of the system in very critical industrial sectors.

Furthermore, the integration of ergonomics computational tools with a simple task definition and time measurement function completes the productivity-ergonomic analysis with well-known benefits as illustrated by Battini, Faccio, Persona, and Sgarbossa (2009), covering all the most relevant factors, such as: posture, frequency, force, recovery and environmental, with a dynamic analysis of the entire body.

4. Real applications and results

The developed integrated system has been applied to two different real cases regarding respectively a distribution center of goods for the fashion industry and a supermarket warehouse for the parts feeding for a mixed model assembly system. These two applications have permitted to test the system in a wide range of warehousing activities, from the simple retrieval of goods inside stocking area to the packing of shipping box. Moreover, the handled pieces were characterized by different dimensions, small items or long and big ones.

Some important considerations have been carried out and the validity of the system has been demonstrated, both for its use as tool assisting the engineers during the design process of warehouses and for the feedback in real-time to workers avoiding the operations in awkward postures.
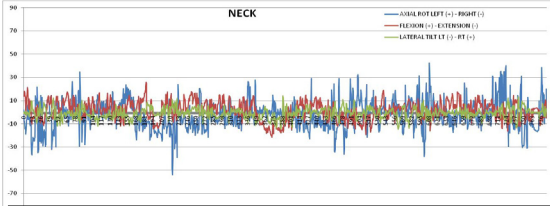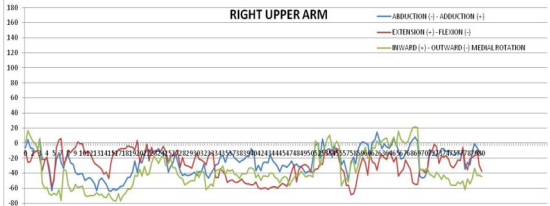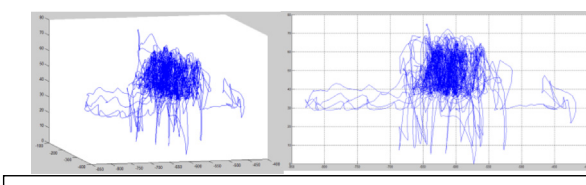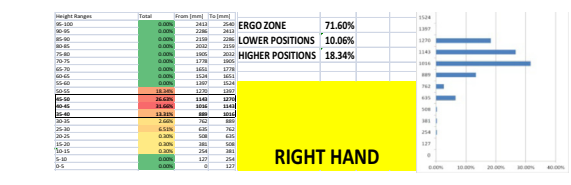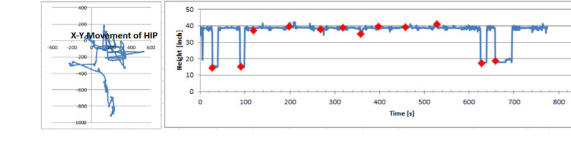
4.1. Distribution warehouses: refilling, picking and packing activities

The first case deals with a distribution warehouse for the fashion industry, where a great number of varieties of small goods are received from the producers. After a quality control phase, the pieces contained in small SKU are stored in a specific stocking area. The objective of this area is to optimize the storage capacity. Then, these pieces are retrieved in a well-defined amount (not in boxes but in the exact required items) from this area to refill the empty locations situated in the picking area. This last zone is smaller than the first one and it contains fewer pieces for each item. In fact, in this area, the main objective is to maximize the throughput of the warehouse, minimizing the travel time spent to pick the items required by a shipping order list. Here the shelves have 7 levels at different heights from the ground. At the end, the picked goods are placed inside the shipping box with the selling cases. This activity is performed in a fixed workstation. In both stocking ad picking area, the storage allocation strategy was random, without any consideration about the item movements items (Battini et al. 2012a; Battini et al. 2013). All the transportation activities from the stocking area to the picking zone are manual with particular big carts pushed by the operators. These carts cannot be used inside the aisles, so the operators leave it in a fixed position outside the storage area and go forwards and backwards to pick or to store the required SKUs or items, involving in an increasing travelled distance. After the refilling, the empty SKUs are pushed away in a garbage zone. From the picking area, the pieces are hand-carried with several problems about the maximum amount of transported pieces.

In this context, the objective of the project has been the redesign of the whole warehouse improving the productivity and

Table 2
Data-analysis tools integrated in the system.

Tools	Scope and measured index	Example of figures	Used joints and/or segments (6DoF per joint)	Main limitations and alarms
Real-Time RULA Tool	Evaluation of RULA INDEX trough the analysis of the UPPER BODY	Joints measurements over time: e.g. neck angles	JOINTS: head, neck, right shoulder, right arm upper, right forearm, right hand, left shoulder, left arm upper, left forearm, left hand, spine 1 (upper), hips (root)	Some evaluated angles: upper arm abduction, neck twist or side bending, trunk twist or side bending and others.
Real-Time OCRA Tool	Evaluation of the AKWARD POSTURE PARAMETER of OCRA INDEX trough the analysis of the UPPER BODY	Joints measurements over time: e.g. right upper arm angles	JOINTS: right shoulder, right arm upper, right forearm, right hand, left shoulder, left arm upper, left forearm, left hand, spine 1 (upper), hips (root)	Head, neck and trunk position.
Real-Time OWAS Tool	Evaluation of OWAS INDEX trough the analysis of the FULL-BODY	Joints and segment measurements over time: e.g. arm and hand position	JOINTS: head, neck, right shoulder, left shoulder, spine 1 (upper), hips (root), right upper leg, right leg, right foot, left upper leg, left leg, left foot SEGMENTS: right and left hands positions	Lateral bending, trunk extension, sit or lie on floor, crawl.
Real-Time LIFTING INDEX Tool	Evaluation of LIFTING INDEX trough the analysis of the UPPER BODY and hand positions	Joints and segment measurements over time: e.g. arm and hand position	JOINTS: right shoulder, left shoulder, spine 1 (upper), hips (root) SEGMENTS: right and left hands positions	Single hand lifting, carrying, type of grip and others
Real-Time HAND Tool	POSITIONS Tool	Evaluation of hand positions in time and executed task Segment measurements over time: hand position frequency	SEGMENTS: right and left hands positions	–
Real-Time HIP MOVE-MENTS Tool	Evaluation of hip movement in time and executed task	Segment measurements over time: hip position on plane and on space	SEGMENTS: hip positions	–
Real-Time TIME&METHODS Tool		Collection of time and modality of execution of analyzed tasks		

the ergonomics of the operators, maximizing the storage capacity. For this reason, the new integrated system has been applied using several ergonomics evaluation tools and tasks' time and methods analysis focused on the most important tasks, which are refilling, picking and packing ones.

In detail, the refilling activity has been analyzed using OWAS as main ergonomics assessment method, due to the necessity to evaluate the full-body postures. It has been coupled with the calculation of travelled meters to understand the total amount of time spent to collect the required SKUs, with the number of lowering and lifting index due to take the SKUs in the lower stocking levels and finally with the percentage of hand positions in no-ergonomic zone during both the collecting of SKUs in stocking area and the refilling of empty locations in picking zone.

Table 3
Summary of results of case 1.

Critical tasks	Description	Ergonomics evaluation methods	Ergo-index (as is scenario)	Problems	Ergo improvements	Ergo-index (to be scenario)
Refilling	In the stocking area, the operators retrieve the SKUs to be placed in picking zone and put them into manual carts, placed outside the stocking area	Full-body postures (OWAS)	% in OWAS risk zone [25%]	High travelled distance		% in OWAS risk zone [5%]
	Then the workers transport all the SKUs in the picking zone	Vertical hip movements [NIOSH]	N° of lowering [5 per order] Lifting index [0.8]	High number of retrievals in bad postures, due to numerous slowing	New class based storage of stocking area with time and ergonomics considerations	N° of slowing [1 per order] Lifting index [0.5]
	Here they refill the empty locations as indicated by the refilling list order, with the pieces contained in the SKU.	Hand positions	% in non ergonomic zone [36%]	Not ergonomics transportation of SKU from stocking area to the carts	New smaller and agile carts for transportation of pieces from stocking area to picking zone	% in non ergonomic zone [23%]
	Finally the empty SKUs are put away	Horizontal hip movements [Travel distance measurement]	Travelled meters [230 m per order]	Difficulties in the refilling activities due to the presence of empty SKU and random storage allocation policy	New reusable-SKU with optimal dimension	Travelled meters [170 m per order]
Picking	The workers pick the parts in the picking zone with returns policy They put the collected pieces into the packing workstations	Full-body postures (OWAS) Vertical hip movements Hand positions	% in OWAS risk zone [40%] N° of lowering [17 per order] % in non ergonomic zone [58%]	Bad postures in picking activities from lower and higher locations due to random storage allocation policy	New class based storage of picking area with time and ergonomics considerations New optimal dimensions of SKU and picking locations	% in OWAS risk zone [12%] N° of lowering [5 per order] % in non ergonomic zone [21%]
		Horizontal hip movements [Travel distance measurement]	Travelled meters [120 m]			Travelled meters [85 m]
Packing	The parts are combined with packages inside the shipping boxes in the packing workstations	Hand Positions	% in non ergonomic zone [27%]	Difficulty to pick the packages in the workplace due to their bad allocation	Redesign of packing work place	% in non ergonomic zone [6%]
		Upper-body Postures (RULA and OCRA)	RULA index [5] OCRA Akward Posture Parameter [0.58]		New allocation and management of all packages	RULA index [2] OCRA Akward Posture Parameter [0.8]

For the picking activity, a similar analysis has been carried out, measuring the travelled meters performed for each order list, the number of lowering and the position of hands during the execution of this activity. Also in this case a general OWAS analysis has been applied, while the Lifting index has not been used due to the very light picked objects.

Finally, in the packing workstations, where the activities are performed in a fixed position, an ergonomics evaluation just for the upper-body has been carried out, using RULA and OCRA methods. Also in this case, the hand positions during the execution are collected and analyzed.

Thanks to these integrated analysis, the most critical aspects which influence the productivity and ergonomics in refilling and picking activities have been highlighted, such as the high travelled distance between the areas, the relevant number of bad postures due to random allocation of SKUs and items in the shelves, the difficulties in transportations of SKUs using the available carts and the presence of empty SKUs to put away. Furthermore, the application of the developed system in the packing activity has demonstrated that the workstations were not designed for that task, involving in high presence of awkward postures during the performing of this kind of activity.

The feedback given from these analyses has permitted to define appropriate suggestions to take into account in the re-design of the warehouse. In fact, the new alternatives of stocking and picking layouts and packing workstations have included the following improvements. Firstly a class based storage allocation strategy in both zones has been introduced, considering both time optimization and ergonomics evaluations, defining some golden zones where the SKUs or the items are more easily reachable in terms of time and posture. Moreover, the transportation between the area have been improved introducing a different kind of cart, smaller and more agile, that permits its use also inside the aisle, optimizing both the travelled distance and eliminating the critical postures.

Generally, a new kind of SKU has been developed with optimal dimension to facilitate the picking activities. Furthermore, it has been chosen a reusable type of SKU in order to eliminate the putting away of empty boxes after the refilling.

Regarding the packing workstations, a new layout of the work place and a new management of all packages items have been proposed. Also with these actions, the jointly optimization of time and ergonomics aspects has been reached. Moreover, in this phase the real-time feedback for the operators has been used and it has permitted to define the better ergo-zone for each worker and to show to the correct execution of the task.

4.2. Supermarket warehouse for high-productive assembly lines

This application regards a well-known type of warehouse, used for the feeding of modern assembly systems, called supermarket warehouse. The assembled products are refrigerated cabinets for the food and beverage sectors, characterized by a great number of components with different dimension and weight.

So in this kind of warehouse, closed to the assembly lines, many different items are stocked in small quantities representing a decentralized in-house logistics area for intermediately storing parts (Battini et al., 2009; Battini et al., 2012a; Battini et al., 2013).

Table 4
Summary of results of case 2.

Critical tasks	Description	Ergonomics evaluation methods	Ergo-index (as is scenario)	Problems	Ergo improvements	Ergo-index (to be scenario)
General picking	The workers pick the parts as indicated on the picking list using a cart. The pickers collects all the parts contained in the list independently by their dimensions and belonged class-requirement	Full-body postures (OWAS) Horizontal hip movements [Travel distance measurement] Vertical hip movements [NIOSH]	% in OWAS risk zone [43%] Travelled meters [310 m per order] N° of lowering [13 per order] Lifting index [0.86]	Hard finding of parts due to random and not fixed parts allocation Hard pushing and pulling due to heavy weight of cart High travelled distance	Introduction of fixed allocations New class based storage of picking area with time and ergonomics considerations New optimal dimension of SKU	% in OWAS risk zone [23%] Travelled meters [260 m per order] N° of lowering [8 per order] lifting index [0.63]
Picking of long parts	The workers pick the long parts in different way depending on horizontal and vertical placement	Full-body postures (OWAS) Hand positions	% in OWAS risk zone [63%] % in non ergonomic zone [67%]	Bad postures due to the picking of parts stocking in horizontal way	New stock modality for most requested parts	% in OWAS risk zone [35%] % in non ergonomic zone [28%]
Picking of small parts	The workers pick the small parts from several location with random storage	Full-body postures (OWAS) Hand positions Upper-body postures (RULA and OCRA)	% in OWAS risk zone [32%] % in non ergonomic zone [29%] RULA index [4] OCRA akward posture parameter [0.63]	Hard to find small parts due to great number of different codes and random allocations Some parts are supplied from the producers in packages not optimized for the picking	New ergonomic area for kitting preparation of small parts New packaging for some purchased parts	% in OWAS risk zone [11%] % in non ergonomic zone [8%] RULA index [1] OCRA akward posture parameter [0.86]

In this context, the operators pick the required parts as indicated on a picking list. They use a cart to collect the parts and to move inside the supermarket warehouse. They collect the components without considering their dimensions and weight, just following the picking list. Moreover, also in this case, the storage allocation is random, so the operators are forced to travel all the aisles of the warehouse to collect the necessary items. Another important aspect is that there is not accurate and real-time updated warehouse management software due to respectively: presence of wide locations, of about 3 meters, and not unique link between one item to one location, but each part can be stocked in different locations, increasing the complexity of execution of picking.

Then, the long parts (more than 3 m long) can be stocked in vertical or horizontal way depending by a previous evaluation made by the operations managers, based on kind of part without considering time and ergonomics impacts. On the other hand, the small parts present a great variety of SKUs, mainly based on type of supplier, but also for this kind of part the dimensions and positions of SKU are just defined by the supplier without considerations about the successive picking activities.

After collecting all the parts included in the picking list, the operators carry the cart to a specific zone. If some parts are not found, the incomplete cart is put in another defined zone waiting to be completed.

Starting from this situation, the scope of the project has been the re-design of the area and especially the definition of new management of parts and their packages for picking.

Also in this case study, the use of the developed integrated system has permitted to highlight where to work in a more accurate manner, optimizing jointly productivity and ergonomics.

In detail, a general full-body analysis based on OWAS method has been carried out initially for all general picking activities and then more accurately for only long and small parts.

Moreover, the movements of hip are collected and analyzed in order to estimate the total travel distance and the number of lowering. The hand positions investigation completes the global application of the system to this real case.

From the use of the integrated system, some relevant problems to be eliminated or reduced have been defined, in order to increase the productivity considering also the ergonomics aspects.

From the general analysis, one of the most critical aspects is the difficulty to find the parts due to random and not fixed parts allocation that involve in high travelled distance and not optimal picking from an ergonomic point of view.

Consequently, in the new alternatives of supermarket warehouses, some improvements regard the introduction of fixed allocations with unique link to the stocked part, and the adoption of class based storage in order to stock the more requested parts in the most accessible locations, and finally for some item a new optimal dimension of SKUs has been defined. All these actions have permitted to reduce the time to pick and to increase the ergonomics.

In detail, from the analysis of picking of long parts, a critical comparison has been carried out between the collection of long parts stocked in vertical and horizontal way. In this case the vertical stocking system is preferable for the more requested items and especially for the heavier parts. About the picking of horizontal pieces, a visual feedback has been given to the operators in order to show them the best ergonomic modality to perform that activity.

On the other hand, about the picking of small parts, the application of the developed system has shown the difficulty to find small parts in wide locations and in some cases the difficulty to pick the items due to their packages, not optimized for the picking.

In this case, for the more requested items a special zone has been created where an operator creates the small parts kits required by the pickers. This area and the workplace, where the operators prepare the kits, have been optimized based on time

and ergonomic point of view, using also a visual feedback for the operators to demonstrate the most correct management of parts in that zone.

5. Conclusions and future researches

This research presents an innovative real-time system for the integrated evaluation of manual task analysis (time and methods) and ergonomics objective assessment of the postures taken by the workers during the execution of operations.

Its potential, compared to previous researches presented in literature (Vignais et al., 2013), is mainly based on the using of a full-body motion capture system, composed by a wearable suit with 17 inertial sensors, integrated with a set of real-time data analysis tools that permits its application in a wide range of industrial sector and operations, such as warehousing, productions and assembly systems, manual workstations and others.

In this paper, the application of this system in warehouse environments is illustrated due to their complexity. In fact, the manual handling activities, typical of warehousing systems, interest the movements of the entire body of the workers and they require the simultaneous use of different types of ergonomics evaluations methods in order to complete their assessment.

Moreover, the ergonomics analysis has been integrated with a developed specific data analysis tool for the real-time collection of tasks time and the methods used to perform them. A specific module helps the users select the most suitable ergonomics methods and sets a series of threshold parameters to underline when the chosen method fails and needs a post processing phase. It also introduces several additional factors settable by the users to consider these limitations inside the real-time evaluations.

This integration permits to make the analysis more accurate and helps the decision makers to achieve the final scope using a win–win approach optimizing productivity and ergonomics aspects (Battini et al. 2009).

As demonstrated by the literature (Vignais et al., 2013), it is important to give a certain feedback to the users from this kind of system. In this research, all the ergonomics evaluation tools are characterized by colored scaling indices available in real-time, in portable screens for the workers or in a virtual 3D environment for managers and engineers.

The application in two real case studies has demonstrated the validity of the systems reaching important results in productivity increases and ergonomics improvements both in the re-design of the warehouses and in the training of human in the execution of the most critical manual tasks.

Future researches will be focused on the integration of the system with several light sensors for the electromyography (EMG), able to collect the data about the real muscles activity and then the real applied strength during the handling of loads. More improvements will be necessary on the tool for the time and method task analysis, developing an automatic procedure to collect this information with advanced technologies as voice command and control.

Acknowledgments

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