EVALUATION OF MANUAL WORK USING SYNCHRONISED VIDEO RECORDINGS AND PHYSIOLOGICAL MEASUREMENTS

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Abstract

Industrial interventions that focus on increased productivity may impair the ergonomics, on a workstation or individual level. This paper presents a method that characterises work time consumption and physical work load of manual work, using video recordings synchronised with physiological measurements of e.g. muscular activity, and postures. The underlying idea was that it is possible to amalgamate technical and human aspects resulting in a synergetic evaluation. The method was developed through two case studies within the Swedish automotive industry, where manual materials handling was studied. A methodological result was that the synchronising procedure was sufficiently precise to allow work activities to be assigned significantly different levels of physical work load. These different levels may be used to predict physical work load in the design and change of production systems. It was concluded that the method is accurate enough to be a useful tool in industrial interventions.

Keywords: Goniometer; Manual work; Work place design

1. Introduction

Recent efforts to achieve efficient and flexible manufacturing within the industry have explored a number of concepts such as product modularization, outsourcing, group work and design for assembly. In addition, the possibility of automation has increased. However, manual work will still be important in the future, because customised products, with a high product variety produced in small batches, still calls for the human capability of learning and adapting (Shalin et al., 1996). Automated machines will not, within reasonable time, substitute the human being, but the way in which man and machine co-operates will certainly change. Knowledge concerning the interface between man and machines is, accordingly, essential for the factory of the future.

Assembly and materials handling represent areas where work related musculoskeletal disorders (WMSDs) are frequent (Zetterberg et al., 1997; Dempsey, 1998). Repetitive industrial work is associated with an increased prevalence of WMSDs regarding, the low back, neck, shoulders, arms and hands (Kuorinka and Forcier, 1995; Bernard, 1997). Varying degrees of evidence exist that specific risk factors including postures and movements (and their combinations) are causal for the development of WMSDs (Bernard, 1997; SCWWRMI, 1998), and attempts have been made to establish quantitative exposure-response relations (for neck/shoulders and upper limbs, e.g. Marras and Schoenmarklin, 1993; Malchaire et al., 1997; Hansson et al., 2000).

In spite of this knowledge, industrial interventions that focus on increased productivity may impair the ergonomics, on e.g. workstation or individual level. Even industrial interventions, e.g. modifications of work methods that focus on ergonomics often fail in fulfilling their purpose (Westgaard and Winkel, 1997). This may be due to the general lack of scientifically based quantitative guidelines regarding exposure limit values for manual work, and to the facts that the practitioners have to interpret the guidelines and, in practice set these limits themselves. This implies that large industrial projects, like the design of a production system, are in fact progressing with a lack of scientifically based ergonomic guidelines using de facto values derived from industrial experiences.

Knowledge concerning ergonomics used in industrial interventions are mainly derived from experiments in laboratories, experiments that do not fully reflect all aspects of the industrial environment. Of course, laboratory experiments have advantages. They facilitate, for example, detailed studies of various ergonomic factors during controlled conditions. However, extending the laboratory studies to replicate industrial environments is time consuming, costly, and results in many cases in deficient replications. Thus, we have chosen to take advantage of the of authors' varying scientific disciplines and experiences to focus on field studies, and to develop a method that gives precise information from direct measurements in industrial work environments.

Integration of video recordings and ergonomic data has previously been performed by the use of analogue technique and a video-mixer (PIcture Mix EXposure, PIMEX: Rosén, 1993). PIMEX implies that a worker is video recorded, at the same time as the exposure, e.g. the muscular activity is recorded by electromyography (EMG). The instantaneous muscular activity is then represented by the height of a bar, and presented on a video monitor together with the output from the video camera. However, as the data are mixed into the video picture, the measured signal is not available for further analysis of the recorded data. The SYBAR system (Hautus, 1997) integrates digitised video and digitised physiological signals to represent these on a computer screen. The synchronisation is accomplished by using a time code generator for the videotape and to record to same time code, together with the sampled physiological data, on a personal computer. Synchronised measurement data may also be recorded on the audio track of the video systems, using e.g. pulse-code-modulation (Wells et al., 1994) or frequency-shift-keying (Yen and Radwin, 1995). All the above mentioned systems require a data link between the camera and the measurement equipment.

This paper presents a method for characterising manual work, using video recordings synchronised with measurements of physical work load. The underlying idea was that it is possible to amalgamate technical and human aspects trough a combinatorial data collection resulting in a synergetic evaluation that accomplish industrial interventions (Fig. 1). In the method, the video recordings are used to identify the work time consumption of different work activities. The synchronisation of video and physical work load recordings facilitates assignments of detailed ergonomic information to the work activities. The precision of the synchronisation was evaluated.

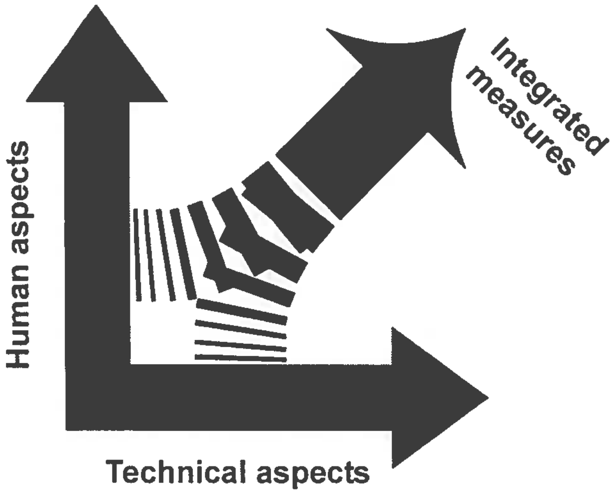

Fig. 1. Schematisation of the idea that it is possible to amalgamate human and technical aspects by integrated measures leading to a synergetic evaluation.

2. Methods

The technical aspects in the underlying idea (Fig. 1) were represented by results from a computer- and video-based observation method for time data collection. While the human aspects comprised physiological measurements of muscular activity, and of body postures and movements.

2.1. Time consumption of work activities

Through previous projects, we have developed a computer- and video-based observation method for time data collection and analysis of work time consumption (Engström and Medbo, 1997). The method involves video recording of a worker, and time coding of the videotape. The observed work is divided into work activities to work elements, materials flow etc. The method, which comprises software and a computer connected to video recorder, may be utilised for different types of analyses, e.g. to measure the efficiency of a production system by separating between value- and non-value-adding work activities by the so-called zero-based analysis. For example, assembly work of different operators in an automotive plant has been analysed (Engström et al., 1997). Hence, this video-based method enables us to define appropriate work activities, the time periods of which are registered in a file with a precision of up to 0.04 seconds (one video frame; standard frame frequency, 25 Hz).

The zero-based analysis compares and measures the level of efficiency in production systems focusing on the time factor. The main feature of the analysis is the ability to compare different production system designs. The method has earlier been applied mainly to assembly work, but it has also proved useful in analysis of order picking systems (Brynzér et al., 1994; Christmansson et al., 1999).

The result of the analysis expresses the potentials of rationalisation. This method was originally created by Wild (1975) and further developed by Engström and Karlsson (1981). The basic idea of this analysis is to divide the resource consumption into three parts:

- The value-adding work represents the resource consumption in an ideal production system without waste of any kind. This value only depends on the product studied and not on the design of the production system;
- loss inefficiencies (i.e. non-value-adding work); and
- system costs (i.e. facilities).

The loss inefficiencies are expressed as a percentage of the value-adding work, and the system costs are expressed in monetary units. In an analysis covering the loss inefficiencies, the methodology to calculate the resource utilisation relative to the value-adding work allows comparison of the efficiency of different production systems not only producing the same products (e.g. one automobile model), but also products in the same category (e.g. all automobile models). Through comparing the loss inefficiencies between the studied production systems, the individual production system's utilisation of resources and possible or necessary modifications can be settled.

2.2. Electromyography

The electric activity of the muscles was taken as a measure of physical work load. The muscular activity was recorded bilaterally in the shoulders (the trapezius muscles) and the forearms (the extensor muscles) using surface electromyography (EMG). The muscular activity during work was normalised to the maximal EMG (MVE), recorded during maximal voluntary contractions (MVCs). The MVCs were, for the trapezius muscles, performed as arm abductions at 90° in the scapular plane, and, for the extensor muscles, as maximal handgrip tests. For details on skin preparation, electrodes and MVCs, see Åkesson et al. (1997).

EMG was acquired, with a sampling frequency of 1024 Hz per channel, using flash-memory based ambulatory data loggers (Asterland et al., 1996). After recording, data was transferred to a personal computer for processing. The root mean square (RMS) values were calculated for epochs of 128 samples, thus characterising muscle activity with a resolution of 8 Hz (Hansson et al., 1997). Since the raw EMG signal stochastically alters around zero, the RMS calculation is essential. The time resolution, here 0.125 seconds, is set by the chosen epoch length, which in turn determines the variance (short length gives large variance) of each RMS value as an estimator of muscular activity.

2.3. Inclinometry

Inclinometers were used for recording the angle, relative to the line of gravity, for the head, the upper back and both upper arms (Hansson et al., 1992; Åkesson et al., 1997; Hansson and Mikkelsen, 1997). One inclinometer was placed on the forehead, an other to the right of the cervico-thoracic spine at the level of C7-Th1. For the upper arms, the inclinometers were fixed to plastic plates (55 × 27 mm) that were placed along the upper arm, with the lateral edge along the line from the lateral-posterior corner of the acromion to the lateral epicondyle, and the upper edge at the insertion of the deltoid muscle. For the head and upper back, the forward/backward projection of the inclination angle (flexion below) and their time derivatives were used for characterisation postures and movements. For the upper arms, elevation (regardless of direction, i.e., we did not separate between abduction and flexion) was used. The 10th, 50th and 90th percentiles of the angle, and the angular velocity, distributions were calculated. The reference position for the head and upper back (0° flexion) was defined as the position obtained, when the subject was standing upright, looking at a mark at eye-level. The forward direction of the head and back was defined with the subject sitting, leaning straightforward. For the upper arms, the reference position (0° of elevation) was recorded with the subject sitting. The side of the body was leaning towards the rest of the chair, the arm hanging perpendicular over the rest of the chair, and with a dumbbell of 2 kg in the hand.

2.4. Goniometry

Wrist positions and movement, for both flexion/extension (flexion) and ulnar/radial deviation were recorded for both the right and left hands. Biaxial flexible goniometers (M110 or XM65, Biometrics Ltd., Blackwood, Gwent, UK) were placed over the wrists (Hansson et al., 1996; Åkesson et al., 1997; Hansson and Mikkelsen, 1997; Stål et al., 1999). The reference position, (0° flexion and deviation) was recorded with the subject standing and with the arms and hands hanging relaxed alongside the body. The flexion measures were chosen for characterisation of the positions and movements. For goniometry and inclinometry data were sampled with a rate of 20 Hz using ambulatory data loggers (Asterland et al., 1996).

2.5. Synchronisation of work activities and physiological measurements

To facilitate synchronisation of the video recording with the physiological measurements, a remote-control-unit was used to mark a sample in the logger and activate a light emitting diode at the beginning of each video recording period. The video frame of this event was identified in the video-based method, which was also used to identify the time-windows for a set of defined work activities. These time-windows were, after a digital synchronisation to the logger data, used to extract statistics, e.g. mean values, 10th, 50th and 90th percentiles, of muscular activity for the different work activities. For these calculations, a macro was written in Microsoft Excel. Moreover, to observe the EMG during specific situations, the synchronisation made it possible to use Synchronised Exposure and Image Presentation (SEIP); a computer program that displays EMG next to the video image on a computer screen (Forsman et al., 1999).

For evaluation of the synchronisation error, the remote-control-unit and the light emitting diode were also activated at the end of the video recording periods, i.e., when the recording was stopped, for exchange of accumulators and videotapes, or for other reason, (e.g. coffee breaks during work). The time-drift, between the video system and the two EMG data loggers was calculated. The error of the sampling frequency of the data loggers was, by recording a reference signal, estimated to <100 ms/h.

3. Application

The method was developed through two case studies within the Swedish automotive industry, where manual materials handling work, i.e. kitting of materials (Christmansson et al., 1999), was studied. The studies were carried out in two parallel product flow automobile plants (i.e. a small work group assembles complete automobiles). In such a plant materials feeding techniques calls for kitting of the materials, i.e. composing kits of materials, for each individual product, by picking components from storage packages to picking packages. There are two principally different kitting methods, (1) conventional picker-to-part and (2) part-to-picker. The last kitting method has proved to have an efficiency potential (Brynzér et al., 1994), it was also used in both plants.

To evaluate the kitting work it was necessary to divide the observed work into specified work activities. A goal was to assign these work activities (in addition to process properties) detailed ergonomic properties. Twenty-five different activities were forming five groups of direct and indirect work activities related to value- and non-value-adding work. The five groups were: Core picking; Handling and transportation; Handling of packaging; Administration and miscellaneous work; and Disturbances. The group ‘Core picking’ includes value-adding work, represented by the activities ‘Grasping of materials from storage package’ and ‘Placing of materials in picking package’.

Simultaneous video recordings and physiological measurements were performed for 11 material pickers for 4 to 5 hours for each picker. Through combining the occurrences of the work activities with the synchronised measurements, statistics of physical work load was calculated for the different work activities (see Christmansson et al., 1999). Extracted results are presented, as an illustration of the method.

4. Results

Using the synchronising procedure (see 2.5) it was possible to link detailed physical work load measures to specific work activities, which showed, for instance, an increased EMG activity in the trapezius muscles during value-adding work activities. The work time consumption and the analyses of physical work load were first carried out separately. Identification of the specific video-frame that corresponded to the marked sample required about ten minutes of manual work. After that, the integrated analyses required approximately ten minutes in execution time for the Excel macro. Fig. 2 illustrates an intermediate step where the occurrences of work activities and physiological data are set to a common time axis. Fig. 3 shows an example (the same subject as in Fig. 2) of a diagram including both accumulated time consumption per work activity group, and physiological data. The statistics of physiological data was based on the subject's total measurement time (5 hours). The median duration of a work activity, i.e. the time between the start of one activity and the following (cf. Fig. 2), was 27 seconds. Including running the written macro, approximately half-an-hour was required to obtain diagrams of the kind shown in Fig. 3.

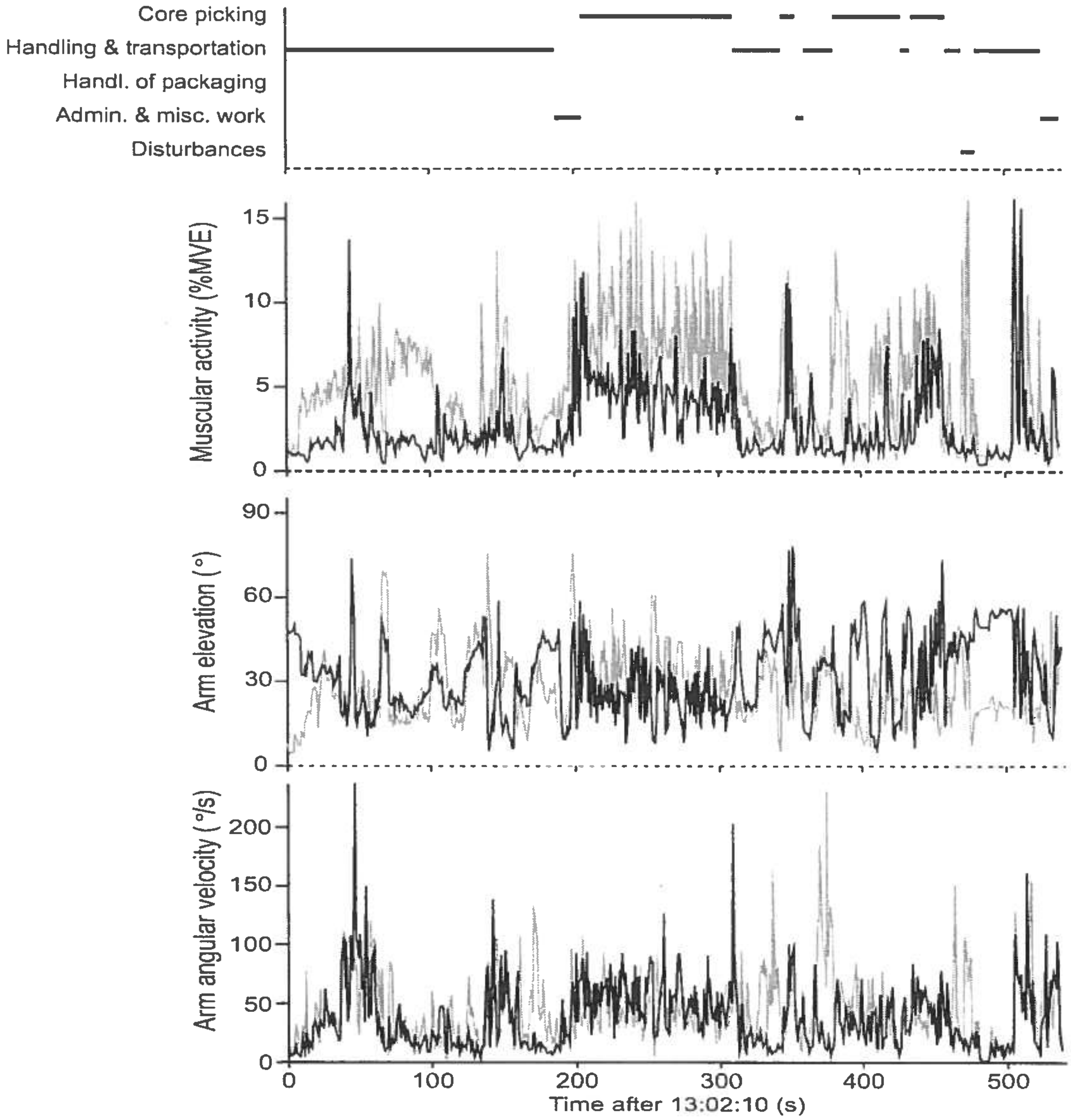

Fig. 2. An example of occurrences of activities in the five groups of work activities, and in grey and black curves for left and right hand side, respectively: EMG from the trapezius muscle, arm elevation, and arm angular velocity for one picker. The graph shows 9 minutes of the total measurement time of 5 hours. The time resolution of the displayed data is 1 second and the absolute value was used for velocity data.

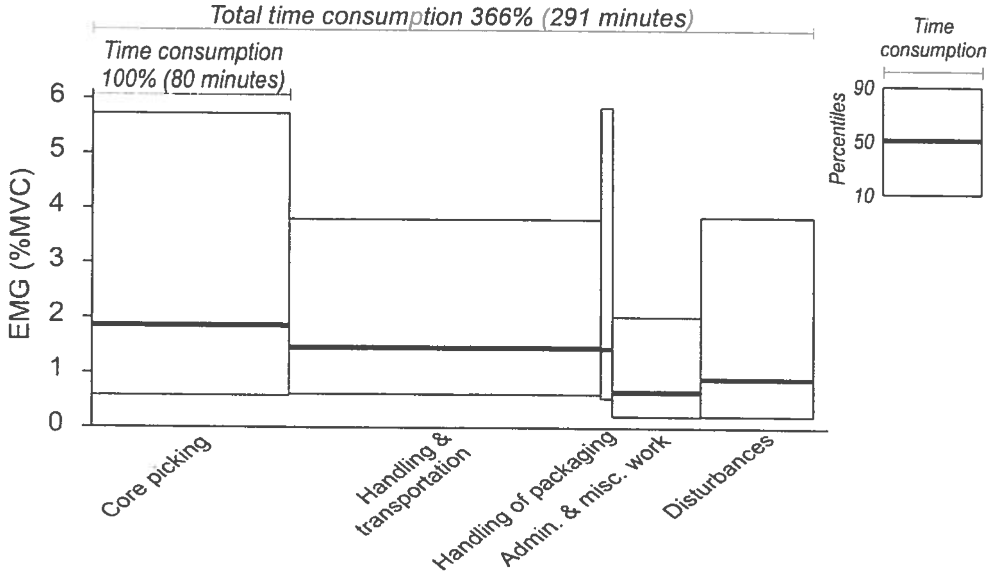

Fig. 3. Integrated analysis of 5 hours work for one material picker. The 10th, 50th and 90th percentiles, of the picker's muscle activity of the right shoulder muscle, are shown for each of the five groups of work activities. The width of the each bar represents the work time consumption of the activity group. 'Core picking', the value-adding work, represents the resource consumption in an ideal production system without losses of any kind. In accordance with the zero-based analysis, the accumulated time of the value-adding work is set to 100%. The other activity groups represent non-value-adding work.

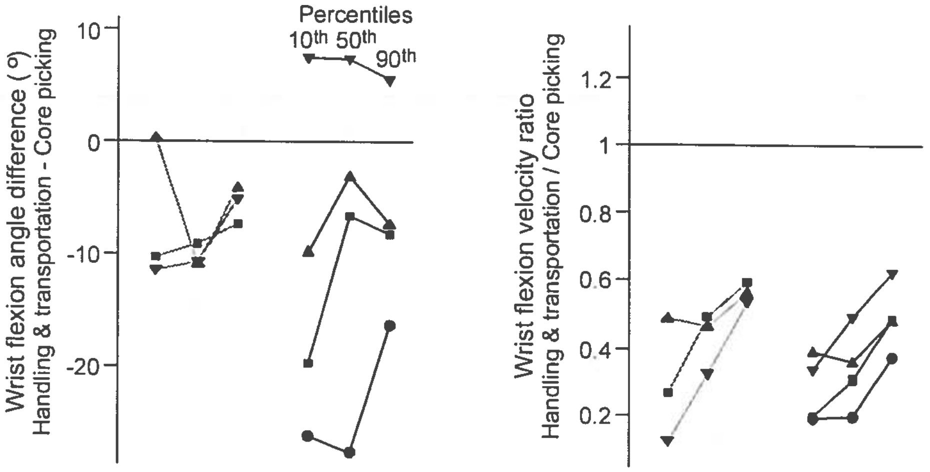

Fig. 4. Presentation of the difference between two work activity groups ('Handling and transportation' compared to 'Core picking') regarding wrist flexion angles and velocities (grey and black curves, left and right hand, respectively) for four pickers (various symbols; the left hand recording was lost for one of the pickers). For angles, the 10th percentile is the dorsal position, and the 90th percentile the palmar position, which has been exceeded for 10 % of the time and the 50th percentile represent the median position of the wrists. For velocities, the percentiles represent the amplitude distribution of the absolute value of angular velocity. Hence, (since positive angles denote flexion in the palmar direction) both hands were, in general, held in more dorsal positions, and the dynamic demands were considerably lower during 'Handling and transportation'.

Over four hours of recordings, including interruptions in the video recordings~~,~~ and exchange of memory cards for the ambulatory data loggers, an over-all synchronisation error of approximately 1 second was introduced, when the synchronisation between the ambulatory data logger and the video recording was executed just once for each video recording period. Simulations of synchronisation errors of ±1 second showed a low sensitivity to the synchronisation timing error on the derived physiological measures in the present data.

The drift between the video system and the loggers was about 400 ms/h and the drift between the two loggers about 20 ms/h. Thus, for shorter periods (less then 5 minutes) without interruptions, synchronisation between the video recordings and the loggers was obtained with an accuracy of one video frame (40 ms). This accuracy could also be obtained over four hours of recordings if synchronisation between the video recordings and the data loggers was executed after every interruption and for every 5th minute.

5. Discussion

By using the presented method, precise information regarding physical work load and time consumption may be derived for various work activities that are relevant regarding productivity. For example, from Fig. 3 it is obvious that a reduction of the time spent with 'Administration and miscellaneous work' will increase the load for the right trapezius muscle, regarding the 10th, the 50th as well as the 90th percentiles. By time weighting, the physical work load can be derived, as function of the relative work time consumption for the work activities. Hence, our method may be used for prediction of physical work load in the design and change of production systems. However, the accuracy and precision of such predictions have not yet been evaluated. Moreover, this time-weighting may be used for estimating the 'ergonomic cost' for the manufacturing of a product in a specific production system. Hence, traditional ergonomics, focusing on reducing individual peak loads (Westgaard and Winkel, 1997), may be broadened to include aspects of work group ergonomics, at both the individual and the collective level.

Johansson et al. (in press) proposed a method to estimate physical work-load dose (WLD) and time consumption for manual work. Their concept is similar to ours, although they used their method to compare alternative designs of materials flow systems. However, their interest was average load and they suggested observational or self-assessed methods for estimation of physical work load. In contrast, in the presented method, physical work load, including, not only the average load, but also the distribution of the load (as represented by the 10th and 90th percentiles) was obtained from actual data. Moreover, data on variation, regarding both time consumption and physical work load, for repeated performances of the same work activity, may be derived. Further, interindividual differences in the work load pattern (which might be considerable, e.g. Balogh et al., 1999) may also be derived, cf. Fig. 4. Thus, the data may be more relevant, and lead to more accurate and precise predictions of both time consumption and physical work load in, e.g. the design of a new production system. Of course, the data acquisition and analysis is more complex than for observational or self-assessed methods.

With the presented method it is feasible to simultaneously consider muscular activity, postures and movements for more than one body region. This improves the ability to avoid sub-optimisation, which otherwise may occur if the interventions, although they focus on ergonomics, only consider some aspects of the work load. Other measures may also be used, but for practical reason the data collection must be limited to the measurements identified as the most relevant in each specific case.

The methods used in the present work provide quantitative measures of physical work load, comparable to the load of other work tasks. Moreover, some of the methods have also been used in epidemiological studies, and may thus provide some information regarding the risk for development of WMSDs.

The existing systems for integration of video recordings and various signals, mentioned in the introduction, all require transfer of data (e.g. by cable, infra-red or radio-frequency link) between the video recorder and the data acquisition equipment, at the time of the recording. The presented method, as well as an earlier developed method (SEIP: Forsman et al., 1999), does not require any connection between the recording devices, which makes the method flexible and easier to use in an industrial environment. The number of data loggers, and hence physiological measurements, that can be included simultaneously is technically unlimited.

A vital methodological result is that the synchronising procedure was sufficiently precise to allow different work activities to be assigned significantly different levels of physical work load. It was concluded that the presented method was accurate enough to be a useful tool in, e.g. industrial interventions.

The human and technical aspects in Fig. 1 are, in the diagram of Fig. 3, represented by muscular activity, and work time consumption, respectively. Other diagrams (not shown, for space reasons), including, for instance, head inclination and arm elevation for the different work activities, were also obtained using the same synchronisation procedure. These diagrams exemplify how, with a minor extra effort, compared to separate analyses, it is possible to integrate, in a synergetic way, human and technical aspects resulting in a synergetic evaluation that accomplish industrial interventions.

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